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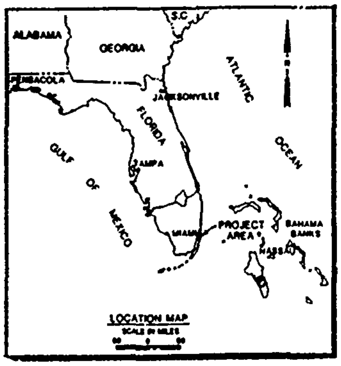
TECHNICAL REPORT HL-91-6

US Army Corps of Engineers

SHIP NAVIGATION SIMULATION STUDY MIAMI HARBOR NAVIGATION IMPROVEMENT PROJECT, MIAMI, FLORIDA



by

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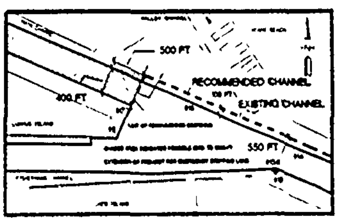

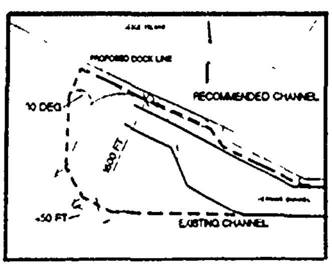

April 1991

Final Report

Approved For Public Release; Distribution Unlimited

HYDRAULICS LABORATORY

Prepared for US Army Engineer District, Jacksonville
Jacksonville, Florida 32232-0019

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1991

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Ship Navigation Simulation Study, Miami Harbor Navigation Improvement Project, Miami, Florida

5. FUNDING NUMBERS

6. AUTHOR(S)
J. Christopher Hewlett

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station, Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report HL-91-6

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAED, Jacksonville, PO Box 4970, Jacksonville, FL 32232-0019

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
A real-time ship simulation study of the proposed design for deepening the Entrance Channel and Fishermans Channel in Miami Harbor, Florida, was made. The purpose was to determine whether deeper draft containerships could enter the harbor safely. The study showed that even with bend easements in certain critical areas, the deeper/heavier proposed ships would have difficulty entering the harbor under certain wind and tide conditions. Tidal current data for the simulation were obtained from a numerical model and were supplemented with prototype measurements.

14. SUBJECT TERMS
Channels (Hydraulic engineering)
Miami Harbor (Florida)
Ship maneuvering
Simulators

15. NUMBER OF PAGES
209

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

PREFACE

This investigation was performed by personnel of the Hydraulics Laboratory of the US Army Engineer Waterways Experiment Station (WES) as authorized by the US Army Engineer District, Jacksonville (SAJ). The study was conducted with the WES research ship simulator. SAJ provided the essential field and model data required.

The investigation was conducted during the period November 1989 to October 1991 by Mr. J. Christopher Hewlett of the Navigation Branch, Waterways Division, Hydraulics Laboratory, under the general supervision of Dr. Larry Daggett, Chief of the Navigation Branch, and Messrs. Frank A. Herrmann, Jr., Chief of the Hydraulics Laboratory; R. L. Sager, Assistant Chief of the Hydraulics Laboratory; and M. B. Boyd, Chief of the Waterways Division.

Acknowledgement is made to Mr. Bob Henderson and Mr. Byron Farley, Engineering Division, SAJ, for their cooperation and assistance at various times throughout the investigation. Special thanks should go to the Biscayne Bay Pilots Association for furnishing professional pilots to con the ship during the simulator tests on the WES ship simulator. The numerical models of the design ships were developed by Tracor Hydronautics, Inc., Laurel, MD, under contract to WES. Thanks go to Dr. Abhimanyu Swain of the Coastal Engineering Research Center, WES, who developed the tidal current numerical model which provided data for the simulation.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASURE

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
foot-tons (force)	2,711.6361	joules
horsepower (550 foot-pounds (force) per second per ton (force))	83.82	watts per kilonewton
knots (international)	0.5144444	metres per second
miles (US nautical)	1.852	kilometres
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms
tons (long, 2,240 lb)	1,016.047	kilograms
tons (2,000 lb force)	8,896.444	newtons

SHIP NAVIGATION SIMULATION STUDY

MIAMI HARBOR NAVIGATION IMPROVEMENT PROJECT

MIAMI, FLORIDA

PART I: INTRODUCTION

Miami Harbor

1. Miami Harbor is located along the Atlantic Coast in southeastern Florida. The study area with the existing channel alignment is shown in Figure 1. The navigation study channel includes the Outer Bar Cut, the Bar Cut, Government Cut, Fisher Island Turning Basin (FITB) just east of Lummus Island, Fishermans Channel, and the turning basin south of Dodge and Lummus islands. The navigation study did not include the Main Channel leading to the presently used "downtown" turning basin near Watson Park. The primary commercial activity in the harbor is the Port of Miami's container terminal on Lummus Island. Presently, containerships up to 960 ft* in length load and unload containers at the terminal using moveable gantry cranes. Miami Harbor's popularity with container companies continues to grow primarily because of the very short run from Atlantic Ocean deep water to the container terminal on Lummus Island. Commercial activity other than the container business includes a burgeoning recreational cruise ship trade and a small amount of trade in petroleum products. In addition to the commercial traffic, Miami Harbor supports a large volume of small boat traffic. This leads to very congested conditions in the FITB, made worse by ferry traffic traveling to and from isolated Fisher Island. These ferries leave on a frequent schedule from either the construction industry's terminal on the northern side of Lummus Island or from the passenger terminal near Causeway Island. At times there can be three ferries, numerous small craft, and a large passenger cruise ship or containership simultaneously passing through the FITB.

2. In the existing condition, the entrance channel, or Outer Bar Cut, extends from project authorized depth in the Atlantic Ocean for 1.5 nautical miles (n.m.) at a true heading of 250 deg. At the end of this reach the

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* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

channel bends to the right, resulting in a 45-deg direction change into Government Cut (295 deg true) and extends approximately 1.4 n.m. to the FITB at the intersection of Main and Fishermans Channels. At the seaward end of Government Cut the channel passes between north and south jetties that extend seaward from Miami Beach and Fisher Island, respectively. Although the constructed length of both of the jetties is approximately 2,000 ft, the north jetty protrudes farther east because of the location of its originating point. On the other side of the FITB, the Main Channel extends at approximately the same heading to the turning basin adjacent to downtown Miami. The majority of the cruise ships out of Miami leave from facilities along Main Channel. Fishermans Channel branches off from Main Channel via a 25-deg left turn and passes alongside the container terminal on the south side of Lummus Island. This channel then extends approximately 1.3 n.m. on a nearly straight course before making a 25-deg bend to the right into the turning basin south of Dodge and Lummus islands.

3. In the existing condition the channel is generally 500 ft wide with 40-ft depth outside and 38-ft depth inside the jetties, below mean lower low water (mllw). The existing channel is wider than 500 ft in the turning basins and the entrance channel bend, and is constricted to 400 ft where Government Cut joins FITB. It should be noted that the existing FITB configuration used in the simulation tests is not entirely federally maintained. The federally maintained Fishermans Channel extends farther into the basin area beyond the eastern end of Lummus Island, and the portion inside this point is maintained by the Port of Miami. This area was dredged by the port to allow additional room for ships to either turn around or make the turn into Fishermans Channel. The authorized width of Fishermans Channel is 500 ft; however, the berthing of containerships at the terminal on Lummus Island reduces the effective width of the channel to less than 400 ft. The 38-ft depth extends only halfway down Fishermans Channel, i.e., far enough to allow large ship access to the container terminal. The remainder of Fishermans Channel is dredged to a depth of 25 ft.

Navigation Problems

4. The Atlantic Ocean-Biscayne Bay tidal exchange through Government Cut has the greatest influence on navigation in the study area. The

concentration of water flow through Government Cut causes high current speeds. The highest current speeds are attained during flood tide and create critical navigation problems. The velocity of ebb tide is slightly less; however, the effect on navigation is comparable in importance. Generally, maximum current speed is on the order of 2.0 to 2.5 knots.

5. Flood tide causes problems at two different locations: at the jetty entrance and at the turn into Fishermans Channel. At the jetty entrance, as stated previously, the north jetty extends farther into the ocean than the south jetty. The flooding tide sweeps around both jetties into Government Cut; however, since the ends of the jetties are at different locations along the channel, inbound ships are affected by asymmetric forces. When entering the jetties, the ship first feels the currents sweeping around the north jetty, which rotates the bow to the south. As it proceeds, the entire ship is affected by the flow around the north jetty and is shifted toward the south. As the ship approaches and passes the end of the south jetty, the flow pushes the bow toward the north while the stern is still being affected by the southward push around the north jetty. This rotates the ship, causing it to end up on the north side of Government Cut, heading toward the FITB. Unfortunately, the pilots prefer to be on the south side of the channel in this reach in preparation for the left turn down Fishermans Channel.

6. Although the problem at the jetty entrance is fully anticipated and compensated for by the pilots, it has a direct effect on navigation at the turn into Fishermans Channel. Conflicting requirements are primarily responsible for the difficulty in navigating between the two locations. The overriding task for a pilot on an inbound containership is to reduce ship speed as much as possible in preparation for the turn into Fishermans Channel. This is especially true during flood tide when slowing down is very difficult because of the push by the following currents. The southward drift and northward rotation of the ship at the jetty entrance require increased engine power to maintain control, thereby causing the difficulty. A ship turning into Fishermans Channel is dominated by a very strong westward drift into the FITB because of the currents and vessel momentum. The process is complicated further because as the bow enters the quiescent water in the lee of Fisher Island, the stern remains in the strong westward currents in line with Government Cut. The resulting rotation compounds the difficulties caused by the drift, and the pilot has a hard time staying clear of the eastern tip of

Lummus Island and straightening up for Fishermans Channel. All this maneuvering has to be done without using very much engine power because of the traffic congestion in the FITB and the presence of docked vessels.

7. This is such a critical situation in the existing channel that the pilots do not attempt this maneuver during strong flooding tide with the largest of the containerships, i.e., the 960-ft vessels. There is anecdotal evidence that a few of the pilots have tried the maneuver in the recent past with almost disastrous consequences. Rather than attempt the left turn under such circumstances, the pilots normally take the ship straight through the FITB into Main Channel, turn at the downtown turning basin, return to Government Cut, and back into the container berth on Lummus Island with assistance from a tugboat. It should be noted that after completion of the deepening project this situation will be even more critical because the proposed deeper draft ships will have no choice but to turn into Fishermans Channel because Main Channel will be shallower. In contrast to large ships, smaller vessels are frequently turned around in the FITB; however, current conditions remain a critical factor in the pilot's decision whether or not to attempt such a maneuver.

8. During ebb tide, navigation difficulties are basically limited to the FITB. Extensive development of causeways and residential islands to the north of the study area has greatly reduced the flow area for tidal exchange, causing most of the water to flow through the open channel in the Causeway Island vicinity (Malloy Channel). The flow from this channel runs across FITB directly toward Fisher Island, dominating the flow coming from Main and Fishermans Channels. Adjacent to Fisher Island the currents turn before sweeping around the point of land at marker 13a (Figure 1) into Government Cut. The primary effect of this current pattern is to push outbound vessels toward Fisher Island and marker 13a. To compensate, the pilots generally steer well to the north upon exiting Fishermans Channel, thereby giving themselves more room to account for the drift and to get lined up for Government Cut.

9. Because containerships, with their high windage area, are prevalent in Miami Harbor, wind is also a critical factor affecting navigation. Wind can cause difficulties for the pilots at any time; however, the most critical period is during inbound runs in flood tide. The problem arises because controlling the ship against the wind is in conflict with the predominant goal for Miami pilots, i.e., slowing the vessels down. This is most critical when

there is a strong beam wind on the ship while inbound in Government Cut. As the pilot reduces propeller revolutions per minute (rpm) to lower speed, the wind has a greater effect and pushes and rotates the vessel. This circumstance requires that the pilot increase ship power to straighten the vessel. Unfortunately, increasing the rpm also increases speed, thereby making slowing down more difficult.

Proposed Channel Improvements

10. Figure 2 shows the four channels tested during the Miami Harbor ship simulation study, one existing and three planned. For all of the planned channels the channel depth was 44 ft outside the jetties and 42 ft inside. The width of Fishermans Channel remained at 400 ft in all the planned channels. The three planned channel configurations are briefly described as follows:

a. The proposed channel shown in Figure 2 is the alignment proposed by the US Army Engineer District, Jacksonville. A widener on the north side of the channel seaward of the jetties increased the width from 500 ft to 800 ft at the ocean end of Government Cut. This widener merged with the existing alignment approximately opposite the end of the south jetty. The channel at the entrance to FITB was widened from the constricted 400 ft in the existing condition to 500 ft with the addition of 100 ft on the north side (buoy 14 side, Figure 1). In this channel the size of the FITB is reduced significantly because the proposed deepening does not extend into the area of the existing turning basin near the eastern end of Lummus Island. Also, this channel featured a new 1,600-ft-diameter turning basin south of Dodge Island in Fishermans Channel.

b. The alternative channel shown in Figure 2 was designed for the pilots to test to determine if the proposed channel was optimum. The entrance bend widener present in the proposed channel was eliminated; however, Government Cut was widened another 100 ft at the entrance to FITB in addition to the widening in the proposed channel, making a total width of 600 ft. This widening took place on the south side of the channel in the vicinity of marker 13a. The configuration of the FITB was essentially equivalent to that of the existing channel, only deepened to 42 ft. Fishermans Channel ended with a 1,400-ft-diameter turning basin south of Dodge Island. The turning basin had the same shape as the 1,600-ft basin in the proposed channel; however, the center of the turning circle was located farther east.

c. The modified 1,400-ft turning basin channel was the same as the alternative channel but with a different shaped turning basin. Essentially, the box-end shape of the other proposed turning

basins was changed by realigning the western edge along a sharper angle to allow more turning room while maintaining the same turning diameter. This channel was designed and implemented during the testing in response to observation of pilot runs in the preceding two channel configurations. A limited number of tests were conducted in this channel at the end of the study.

Scope of Simulator Study and Test Design

11. The ship navigation study was conducted to provide recommendations concerning four questions:

- a. Is a widener needed on the north side seaward of the jetty entrance to compensate for the effect of unequal jetty extension?
- b. What channel width is required at the intersection of Government Cut and FITB to make the turn into Fishermans Channel easier?
- c. What FITB configuration is required to allow safe navigation during the turn into Fishermans Channel?
- d. What configuration is required for the new turning basin in Fishermans Channel south of Dodge Island to allow 960-ft ships to turn around?

Because of their predominance in Miami Harbor, two containership numerical models were used for simulation testing during the study. For the existing channel a President Lincoln class containership with a length overall (LOA) of 860 ft, a beam of 106 ft, and a draft of 34 ft was used. A New York Econo-class containership with LOA of 950 ft, beam of 106 ft, and a draft of 34 ft was also used in the existing channel. The Econoclass ship does not presently call at the Port of Miami; however, a numerical model of the ship was available at the US Army Engineer Waterways Experiment Station (WES) and the dimensions are almost identical to the Maersk Lines, Inc., 960-ft containerships, which do frequent the harbor. The 950-ft test vessel is, by all accounts, less maneuverable than the Maersk Lines ship (which has a bow thruster) and, therefore, provided a critical scenario for the simulations. Furthermore, these ships are actually being used at other ports on the East Coast of the United States and could begin to call at Miami in the future. For the deepened planned conditions the Econoclass ship was used with a 38-ft draft; however, the smaller ship was not tested.

12. For the existing channel the simulation scenarios began in the entrance channel near the sea buoy (Figure 1) and ended in the Fishermans

Channel adjacent to the gantry berths on Lummus Island. The existing turning basin in Fishermans Channel was not tested because the vessels considered in the study are too deep to traverse the present channel beyond the western end of Fisher Island. Inbound runs were tested during flood tide conditions with and without a northeasterly wind acting as a driving force for the current. During the with-wind current conditions, a randomized northeasterly wind with a mean magnitude of 25 knots was also acting on the ship. The particular wind magnitude spectrum used created a gusting wind ranging from approximately 15 to 40 knots. Ebb tide outbound runs in the FITB area were also tested with and without wind blowing on the ship; however, only one set of current data was used because the wind has little effect on the current in the lee of the coastline. The outbound runs started in the Fishermans Channel adjacent to the Lummus Island gantry crane berths and ended in the Government Cut after the ships recovered from the turn at the constriction. The same conditions were tested for the planned channel alignments using the same current data. A few tests were conducted in the proposed channel and the modified 1,400-ft Fishermans Channel turning basin under a 25-knot southeasterly wind condition. For the inbound planned scenarios, the tests continued all the way to the new turning basin south of Dodge Island where simulated tugs (3500 hp available) were used for turning around in the different basin designs. The planned outbound runs covered the same territory as for the existing channel tests. Six professional pilots from the Miami area visited WES and conducted simulation tests. Table 1 summarizes the test conditions and includes the number of runs obtained for each set of conditions. For the existing channel scenario with the 950-ft ship, only a wind direction is listed. After the tests had been completed, it was determined that the longitudinal wind effect on the 34-ft-draft ship simulated a wind speed greater than 25 knots. During the tests the pilots noted the problem because the ship required too much engine power to maintain speed against the wind. The increased effect did not directly impact the lateral drift and rotation of the ship; however, it did affect the speed of the ship. Therefore, these runs conducted with the shallower draft ship constitute a more extreme case than for the deeper draft ship in the planned channels. This was most critical during the outbound runs where the ships started from a dead stop and had to accelerate out of Fishermans Channel directly into the northeast wind.

Table 1

Simulator Test Scenarios

Scenario No.	Channel	Direction of Ship	Ship Dimensions, ft	Current	Wind on Ship Direction	Wind on Ship Speed knots	Number of Runs
1	Existing	Inbound	860x106x34	Flood	None	--	2
2		Inbound		Wind/Flood	NE	25	2
3		Outbound		Ebb	None	--	2
4		Outbound		Ebb	NE	25	6
5		Outbound		Flood	None	--	2
6		Outbound		Wind/Flood	NE	25	5
7	Existing	Inbound	950x106x34	Flood	None	--	6
8		Inbound		Wind/Flood	NE*	--	
9		Outbound		Flood	None	--	
10		Outbound		Wind/Flood	NE*	--	
11		Outbound		Ebb	None	--	
12		Outbound		Ebb	NE*	--	
13	Proposed	Inbound	950x106x38	Flood	None	--	
14		Inbound		Wind/Flood	NE	25	
15		Inbound		Flood	SE	25	2
16		Outbound		Flood	None	--	2
17		Outbound		Wind/Flood	NE	25	6
18		Outbound		Ebb	None	--	6

(Continued)

* See explanation, paragraph 12.

Table 1. (Concluded)

Scenario No.	Channel	Direction of Ship	Ship Dimensions, ft	Current	Wind on Ship Direction	Wind on Ship Speed knots	Number of Runs
19	Proposed	Outbound	950x106x38	Ebb	NE	25	6
20	Alternative	Inbound		Flood	None	--	6
21		Inbound		Wind/Flood	NE	25	6
22		Outbound		Flood	None	--	2
23		Outbound		Wind/Flood	NE	25	6
24		Outbound		Ebb	None	--	6
25		Outbound		Ebb	NE	25	6
26	Modified	Inbound		Wind/Flood	NE	25	1
27	Modified	Inbound		Flood	SE	25	2

PART II: DATA DEVELOPMENT

Required Data

13. Data required for the simulation study included channel geometry, bottom topography, channel currents for proposed as well as existing conditions, maneuvering characteristics of test ships, and visual data of the physical scene in the study area. Dredging survey sheets provided by Jacksonville District were used for the existing channel alignment, and the proposed channel alignment was modeled as designed. Current data were obtained from an existing two-dimensional finite difference numerical model of the Miami Harbor area (Swain 1988). Supplemental current data for the FITB area were obtained from prototype measurements taken before pi˘ot testing began. A reconnaissance trip was carried out for the purpose of observing actual shipping operations in the study area. Video recordings and still photographs were taken during the transits to aid in the generation of the simulated visual scene. Discussions with pilots were also held during this trip so that WES engineers could become more familiar with concerns and problems experienced during shipping operations.

Description of Simulator

14. It is beyond the scope of this report to describe in detail the WES ship simulator;* however, a brief explanation will be made. The purpose of the WES ship simulator is to provide the essential factors in a controlled computer environment to allow the inclusion of the man-in-the-loop, i.e., local ship pilots, in the navigation channel design process. The simulator is operated in real-time by a pilot at a ship's wheel placed in front of a screen upon which a computer-generated visual scene is projected. The visual scene is updated as the hydrodynamic portion of the simulator program computes a new ship's position and heading resulting from manual input from the pilot (rudder, engine throttle, bow and stern thruster, and tug commands) and external

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* "Hydraulic Design of Deep Draft Navigation Channels," PROSPECT (Proponent Sponsored Engineer Corps Training) course notes, US Army Engineer Waterways Experiment Station, Vicksburg, MS, 19-23 June 1989.

forces. The external force capability of the simulator includes effects of wind, waves, currents, banks, shallow water, passing ships and tugboats. In addition to the visual scene, pilots are provided with simulated radar and navigation information including water depth, relative ground and water speed of the vessel, magnitude of lateral vessel motions, relative wind speed and direction, and ship's heading.

Validation and Data Description

15. One of the most important milestones in the simulation process is the validation exercise. During this exercise, pilots from the study area come to WES to conduct simulator tests in existing conditions. The purpose of the tests is to use local pilot expertise to ensure that the simulation is as realistic as possible. While conducting these tests, the pilots pay close attention to ship handling, external force effects, and visual scene objects and make comments and recommendations for improvement. Validation tests usually result in some modifications to the data bases. The five input data bases required to conduct a simulation study for a particular channel are discussed in the following paragraphs.

Test File

16. The test file contains initial conditions (ship speed and heading, rudder angle, and engine setting) for the simulation and geographical coordinates for the channel alignment. The channel is defined in terms of cross sections located to coincide with changes in channel alignment and current direction and magnitude. The information used for the development of the Miami channel data base was obtained from Jacksonville District's project drawings. The Florida state plane coordinate grid was also plotted on these drawings and was used for the simulator data base coordinate system. Also included in the test file are the steepness and height of the banks adjacent to the channel. These data are used by the computer to calculate bank suction forces on the test vessels. Specifications of other external forces such as wind and waves are also included in this file. Also, the definition of an autopilot track-line and commands that control the computer autopilot are included for use in the simulator's fast-time capability.

17. For the Miami project the simulator channel cross sections were placed to mark each bend of the channel and a change in submerged bank conditions or delineate changes in channel width, e.g., where a turning basin opens up on one side of the channel. In straight sections where currents remained fairly constant along the channel, the distance between cross sections was relatively large. Closer spacing was used in areas with significant current variation such as FITB and the jetty entrance. The simulator program interpolates the transitions between cross sections.

18. For the Miami Harbor simulation, wind was one of the most critical factors affecting navigation because of the type of vessel being simulated. A northeasterly wind was chosen for the tests based on discussions with the pilots prior to initiation of the study. This wind direction was considered the most critical for inbound ships. During the discussions, some of the pilots commented that southeasterly winds also were considered critical, especially during turning maneuvers in the Fishermans Channel basin. Due to restrictions on the scope of the study, the testing program concentrated predominantly on the northeasterly wind with a limited number of runs conducted with southeasterly winds.

19. Water depths for the simulator were based on authorized project depths. For the simulated existing channel, the water depth represented the existing condition taken from the most recent dredging survey furnished by the District. In the proposed conditions a 4-ft deepening was applied to the channel depth resulting in a 42-ft depth in the inner channels and a 44-ft depth in the bar channels. Existing depths were maintained in the proposed channels when they were deeper than the proposed depths. Also, bank slopes and water depth in shallower areas adjacent to a channel (overbank depths) are included in the test file. These data are used in the calculation of ship hull bank forces. Briefly, bank forces occur when a ship travels close to a submerged bank, a wall, or a docked ship, and the resulting effect is characterized by a movement toward the bank and a bow-out rotation away from the bank. In many harbors, especially ones with narrow channels, bank effects are an important design consideration; however, they are not a critical navigation factor in Miami Harbor, at least in part because ships are traveling at fairly low speeds (with the exception of outbound ships in Government Cut). Another reason that bank effects are not crucial in Miami is because the effects of currents and wind are far more significant.

Scene File

20. The scene data base comprises several data files containing geometrical information enabling the graphics computer to generate the simulated scene of the study area. The computer hardware and software used for visual scene generation are separate from the main computer of the ship simulator. The main computer provides motion and orientation information to a stand-alone graphics computer for correct vessel positioning in the scene, which is then viewed by the pilot. Operators view the scene as if they are standing on the bridge of a ship looking toward the ship's bow in the foreground. View direction can be changed during simulation for the purpose of looking at objects outside of the relatively narrow straight-ahead view.

21. Aerial photographs, navigation charts, and dredging survey charts provided the basic data for generation of the visual scene. The simulation testing required low visual resolution beyond the immediate vicinity of the navigation channel. All land masses in the vicinity of the navigation channel and all aids to navigation in the vicinity of the study area were included in the scene. Man-made features in the inner harbors that were in the visual scene included docks, buildings, and gantry cranes. Docked ships in the visual scene included a containership moored at the gantry berths on Lummus Island and a tanker at the petroleum storage facility on Fisher Island (Figure 2). In addition to the man-made and topographical features in the study area, the visual scene included a perspective view of the bow of the ship from the pilot's viewpoint. Visual data bases for both design ships were available at WES for inclusion in the simulation.

Radar File

22. The radar file contains coordinates defining the border between land and water and significant man-made objects, such as docked ships and aids to navigation. These data are used by another graphics computer which connects the coordinates with straight lines and displays them on a terminal. The objects viewed comprise visual information that simulates shipboard radar. The main information sources for this data base were the project drawings and dredging survey sheets supplied by the District.

Ship Files

23. The ship files contain characteristics and hydrodynamic coefficients for the test vessels. These data are the computer's definition of the ship. The coefficients govern the reaction of the ship to external forces, such as wind, current, waves, banks, underkeel clearance, and internal controls, such as ruddeı and engine rpm commands. The numerical ship models for the Miami simulations were developed by Tracor Hydronautics, Inc., of Laurel, MD (Ankudinov 1986, 1989). The test ships were chosen based on discussions involving District personnel, WES personnel, and Miami pilots. For quick reference the following tabulation lists the important characteristics of these ships:

Ship Type	LOA ft	Beam ft	Draft ft
Containership	950	106	34/38
Containership	860	106	34/38

Current File

24. The current file contains current magnitude and direction and water depth for each of eight points across each of the cross sections defining the channel alignment. Current data for a ship simulation study are usually obtained from physical or numerical models. In this study, current data were available from a numerical model of the Miami Harbor (Swain 1988), and these data were used as a base from which the currents for the ship simulation study could be built. The numerical model is generally used as a tidal circulation or storm surge model and uses a finite difference scheme. As such, it cannot represent the complex navigation channel layout accurately. In addition, the model study did not involve tests of the proposed navigation channel as tested in the ship simulation study. However, it was decided that due to time and cost constraints, no additional modeling of the currents would be done.

25. Therefore, the existing current data as computed by the numerical model were interpolated to determine the velocities and water depths at each point in the simulation data base for the existing project. Then data for the proposed and alternative channels were developed by adjusting the current

magnitudes in inverse proportion to the change in cross-sectional area due to the deepening and/or widening of the channel. The directions of the currents were not changed. The currents were then checked and adjusted during validation of the simulation model.

26. Runs were conducted with and without a 20-knot northeasterly wind under spring tidal conditions with a range of approximately 3.0 ft. During the simulation validation tests with Miami pilots, much of the time was spent trying to verify the realism of the simulator currents extracted from the numerical model. Currents in the critical areas at the jetty entrance and FITB did not satisfy the pilots and adjustments had to be made. At the jetty entrance the pilots did not feel that there was sufficient current effect on the ship. This problem was remedied by directing the currents at the end of both jetties at a sharper angle toward the center of the channel. Figure 3 shows the current vectors for flooding tide in the existing channel. Furthermore, during outbound runs in FITB the ships did not behave according to the experience of the pilots. A number of different modifications to the currents in this area were attempted without pilot satisfaction. It was decided that the current data in the FITB area needed supplemental verification; consequently, a field crew from WES was sent to the Miami area prior to the start of pilot testing. Field measurements were made by the crew at the jetty entrance during flood tide and in FITB during ebb tide. Results of the field measurements confirmed comments made by the validation pilots. Rather than coming from Main Channel, the predominant flow emanates from the Malloy Channel in the Causeway Island vicinity. The current data base was modified using these new measurements and implemented in the simulator. Figure 4 shows the ebbing current pattern used in the simulator for the existing channel. The same ebb currents were used for the planned channels with only slight modifications to account for the different alignments and channel dimensions.

27. The numerical model (Swain 1988) had very low resolution in the Fishermans Channel turning basin south of Dodge Island. Consequently, current data for use in the simulator data base were sparse in this area. No tests were conducted in this area under existing conditions; however, for the planned conditions, currents had to be estimated using a very small number of data points. Since the new turning basin will be constructed predominantly in an existing shallow-water area, it was assumed that the flood flow from Fishermans Channel expanded into the basin and the velocity was decreased in

inverse proportion to the increase in water depth and width. Figure 5 shows the flood tide current pattern for the District-proposed channel.

PART III: RESULTS

28. Plotted simulator results are cross referenced to the run scenario and plot type in Table 2 and are shown in Figures 6-140. The results analysis for the Miami Harbor focused on three data sources: (a) track-lines, (b) control measures, and (c) pilot questionnaire ratings. The track-line analysis constituted a visual examination of the recorded ship transits while the control measures analysis investigated ship and pilot behavior in more detail. Control measures included in the analysis were channel edge clearances, ship speed, propeller rpm, ship drift angle, rudder angle, and ship rotation rate. In the following paragraphs, results and conclusions from the track-line and control measures analyses are presented, organized according to transit direction. Results from the different test channels are compared during these discussions. The pilot questionnaires focused more on the entire transit rather than on specific areas; therefore, the pilot ratings are more general and are discussed separately based on a comparison of results from the tested channel layouts.

29. Prior to the discussion of results, some explanation is needed to clarify a few specific points concerning the presentation of results. First, the control measures plots shown are composite averages of all pilot runs conducted under the same conditions. For this comparative analysis the control measures were averaged over each 1,000-ft channel section on a by-pilot basis and then these mean values (normally six) were averaged into one value which was then plotted against distance along track at the midpoint of the channel segment. This procedure produced a running average that smoothed out the oscillations of each measure, thereby making trends and patterns more easily discernible. Secondly, the distance-along-track horizontal axis on these plots is drawn based on an inbound run traveling from left to right, in other words toward increasing channel station numbers. Channel distance (stations) is measured beginning at the channel entrance and increasing towards the Fishermans Channel Turning Basin. In the opposite sense, the control measures for outbound runs should be read from right to left, or toward decreasing channel station numbers. Thirdly, the control measure termed maneuvering factor is actually the algebraic product of the rudder angle and rpm values. This value serves as a comparative measure of the amount of ship turning power being used by the pilots.

Table 2

Scenario-Figure Number Cross Reference

Scenario*	Track Plot	Rudder Angle and rpm	Maneuvering Plot Factor	Speed, Rotation Rate, and Drift Angle	Clearances
1	6	17,18	28,29	39,40	50,51
2	7	19,20	30,31	41,42	52,53
3	69	109	117	125	133
4	70	110	118	126	134
5	61	77	85	93	101
6	62	78	86	94	102
7	8	21	32	43	54
8	11	24	35	46	57
9	63	79	87	95	103
10	66	82	90	98	106
11	71	111	119	127	135
12	74	114	122	130	138
13	9	22	33	44	55
14	12	25	36	47	58
15	13	26	37	48	59
16	64	80	88	96	104
17	67	83	91	99	107
18	72	112	120	128	136
19	75	115	123	131	139
20	10	23	34	45	56
21	14	27	38	49	60
22	65	81	89	97	105
23	68	84	92	100	108
24	73	113	121	129	137
25	76	116	124	132	140
26	16	-	-	-	-
27	15	-	-	-	-

* See Table 1 for description of scenario.

Inbound Runs

30. Plots of the composite track-lines for inbound runs in each tested channel are shown in Figures 6-16. These figures are marked according to test channel, type of ship and whether or not wind was included. Figures 17-60 show the control measures plots for the inbound runs, with their respective test conditions.

Entrance channel bend and jetty entrance

31. Comparison of the track-line plots for the wind and no-wind existing channel (Figures 6-8 and 11), alternative channel (Figures 10 and 14), and proposed channel cases (Figures 9 and 12) indicates some advantage to widening the north side of the entrance channel bend. Invariably, in the existing and alternative channels the pilots clipped the northern side of the bend. Wind did not seem to have a large effect on the pilots' abilities to negotiate the bend. According to the pilots, the main problem in the area is an encroaching shoal on the northern side of the channel seaward of the jetty entrance. This shoal is presumably composed of sediment deposited by the strong cross-channel component of the flood currents in this area and reduces the effective channel width to less than the authorized 500 ft. In the simulated existing and alternative channels, the pilots did not have this limitation; therefore, they moved farther to the north and clipped the channel edge in their quest for extra room to allow for the southward push by the currents near the jetty entrance. Some of the pilots stated that the existing 500-ft width would be adequate in this area if it were actually provided, although, as mentioned previously, the existing case simulator track plots show some difficulty in this area even with the entire 500 ft available. The proposed channel plot indicates much better clearance around this bend than in the other channels; however, there was more widening than is necessary.

32. Figures 17-27 show the rudder angle and rpm for the inbound runs. These figures generally indicate little difference in pilot performance in the entrance bend area, regardless of channel design. Comparison of the wind and no-wind cases shows that a higher average rudder was used in the no-wind case. The most probable reason for this is that the general southward push of the wind actually helped the turning process, thereby requiring less rudder movement. The results for ship speed, rate of turn, and drift angle (Figures 39-49) indicate only small differences between the test channels or the

with-/without-wind cases in this particular area. The lower value of drift angle in the existing channel in the Outer Bar Cut is probably a result of the maneuvering characteristics of the 950-ft containership with the shallower draft. Figures 50-60 show the clearances for the inbound runs. At the entrance channel bend the mean starboard clearance approached zero for the existing and alternative channels.

33. The simulation results suggest that widening of 150 ft would be adequate along the north side of the entrance channel bend to compensate for the southward drift experienced by the pilots in the vicinity of the jetties. Details of the recommended widening are presented in Part IV.

FITB and Government Cut widening

34. This area was the most critical section of the study channel. It is very difficult to bring a heavily laden containership of the size tested through Government Cut, slow down prior to entering FITB, and make the left turn into Fishermans Channel. Flooding tidal current, wind, and vessel momentum work against the crucial strategy of slowing down. The track plots for the inbound runs (Figures 6-16) show that only in the existing scenario with the 860-ft containership and no wind (Figure 6) were the pilots able to stay within the channel limits. It should be noted again that in the existing channel the pilots do not attempt such a maneuver under similar conditions with the 950-ft containerships (under some conditions 860-ft containerships are also not turned left into Fishermans Channel). Instead, they direct the ships "downtown" (straight down Main Channel) to the existing turning basin, turn around, return to the FITB and back into mooring position alongside Lummus Island. Therefore, the maneuver with flood tide in the simulated existing channel was carried out only to establish a comparative base case. Some of the pilots stated that in the recent past the maneuver has been tried under real conditions similar to the simulated conditions with almost disastrous results. On the other hand, smaller ships are frequently turned in the FITB and backed into place; however, the pilots still maintain a close watch on tide and wind conditions prior to attempting such moves.

35. After observation of a number of these inbound runs, it became clear that the most critical measure of the success of the run was the speed with which the ships passed through the FITB adjacent to the docked vessels at Fisher and Lummus islands. It was determined that no matter how successful the pilots were in staying within the simulated channel, the run could not be

considered successful if the ship was making too much headway through the FITB. The idea expressed by the pilots was that without the speed limitation they could make the turn into Fishermans Channel with little trouble--at full-ahead. The general consensus among the pilots was that for a large containership, a speed of greater than 5 knots in the FITB would be unacceptable because of the congested traffic conditions and the presence of moored ships. Later in the report a discussion is presented concerning the effect of the passing ships on the moored vessels.

36. The maneuvering factor plots for inbound runs (Figures 28-38) basically show little difference in ship power used between the test channels; therefore, the speed limit and channel edge clearance were considered the most significant factors in this area. On the clearance plots (Figures 50-60) it can be seen that only for the proposed channel did the pilots, on average, go outside the channel limits. However, these average clearances must be considered in conjunction with ship speed to determine transit success.

37. Based on the speed limit of 5 knots, Table 3 summarizes the success of the pilot runs for each set of inbound test conditions. In this table the term good indicates a run in which the ship stayed within the defined channel limits and did not collide with an object, such as a navigation buoy. Great difficulty was experienced by the pilots in the existing channel, with the exception of the small ship case with no wind (scenario 1). The success results for the proposed channel were worse than for the existing channel in the FITB area, albeit more of the pilots stayed within the channel limits. In addition to the northeast wind condition in the proposed channel, Figure 13 shows two runs conducted with southeast wind (speed information not presented) which show just as many problems with the turn. The alternative channel configuration allowed the best overall results, although under wind conditions (Figure 14) a majority of the pilots had too much headway while entering Fishermans Channel.

38. The results clearly show that transits under windy conditions are extremely difficult for the largest containerships. The reason for this is that during the passage through Government Cut the pilots must sustain a certain level of engine power in order to maintain steerage against wind drift. This requirement precludes their ability to get the speed of the ship down to an acceptable level for the turn at buoy 13a (Figure 1) and the passage through the FITB. This explains the reluctance which the pilots presently

Table 3

Inbound Run Success

Scenario No.	Channel	No. of Good Runs	Number of Good Runs With Speed Less Than 5 Knots: Adjacent to Tanker	Adjacent to Containership
1	Existing	2 of 2	2	2
2	Existing	0 of 2	-	-
7	Existing	3 of 6	3	3
8	Existing	3 of 6	0	0
13	Proposed	4 of 6	0	2
14	Proposed	5 of 6	0	1
20	Alternative	6 of 6	5	6
21	Alternative	6 of 6	2	5

have with turning the largest vessels directly into the Fishermans Channel under similar conditions. The analysis indicates that for the large containerships to go bow first into Fishermans Channel, the FITB must at least remain in the existing shape. Also, both sides of the channel at buoys 13a and 14 should be widened. This widening would allow the pilots room to start the left turn earlier while lessening their chances of running the ship's stern into the north bank. Even with this recommended design in place, the study results indicate that these large, heavily laden ships should not be brought in under conditions similar to those tested in the simulation, i.e., strong wind and flood tide. This becomes even more important with the realization that the Main Channel leading to the downtown turning basin will no longer be an escape option (because of shallower depth in the planned condition) in the event that the pilot is not in shape for the turn into Fishermans Channel.

Fishermans Channel Turning Basin

39. Because ships are controlled predominantly by tugs during turning basin maneuvers, analysis of recorded ship control measures are not particularly meaningful; therefore, conclusions concerning turning basin design were made based on the recorded track plots. Figures 9, 10, 12, and 14-16 show the results of the tug-assisted turning maneuver in the different turning basin configurations. Predominantly, the pilots conducted the turning maneuver with

bow to the north using two tugs, one pushing on the starboard quarter and the other pushing on the port bow. One of the pilots positioned both tugs at the bow with one pushing and the other pulling and occasionally a pilot would back down with a tug to slow ship rotation while entering the basin. For the proposed channel (Figures 9 and 12) the turns in the 1,600-ft turning basin were handled without too much difficulty, although a few of the runs did clip the channel edge. The general direction of the drift for the simulated currents was toward the west, creating some difficulty for the pilot if he did not begin his turn at the right time. It should be noted that this is a completely new maneuver with a much larger ship. For the 1,400-ft turning basin in the alternative channel (Figures 10 and 14), the pilots could not keep the vessel within the channel limits even without the wind. One of the primary conclusions from these tests is that the approximate triangular shape of the tested turning basins proved fairly awkward for the pilots to use. Because of the length of the ship, the pilot had to creep up on the center of the turning circle and start turning just at the right moment. If the pilots started the turn too early, they would end up turning in an area of the basin without enough width; if they turned too late, the wind and/or current drift would push them toward the back of the basin before the maneuver was complete. The simulation results suggest that even for the 1,600-ft basin, additional room is needed at the western end because of possible drift caused by wind and current.

40. With the increased cost of this alternative in mind, a modified 1,400-ft turning basin (Figures 15 and 16) was entered in the simulation data bases and was tested to a limited extent with the last two pilots who visited WES. The configuration alleviated the box-end constriction of the other plans but kept the 1,400-ft turning diameter. Figure 16 shows one run in this configuration under northeast wind conditions (as before) with good results. Figure 15 shows two runs under southeast wind conditions with somewhat less successful results. One pilot clipped the back edge of the turning basin and the other almost collided with the adjacent docked ships. However, in the former case the pilot was going too fast and started the turn too late; and the latter case was most likely due to pilot inattention (this was his very last run), both of which could have been avoided. Based on these runs, there is a preliminary indication that the modified 1,400-ft basin plan would be adequate; however, with only three runs to evaluate, it would be inadvisable

to recommend the design change. Therefore, a modified 1,600-ft turning basin is recommended and is detailed in Part IV.

Outbound Runs

41. Figures 61-76 show the composite track-lines for all the outbound runs. These figures include runs in both flood and ebb tide; however, ebb tide was much more difficult for the pilots to handle and is considered the most critical for the purposes of this analysis. The ebb tide track plots are shown in Figures 69-76. Figures 77-140 show the control measures plots for the outbound runs for both flood and ebb tide. It should be remembered that for the control measures plots the outbound runs move with decreasing station values. For all the existing channel ebb tide runs, the track plots (Figures 69-71 and 74) show the pilots steered the ship so far to the north to avoid buoy 13a at the inside corner of the turn into Government Cut that they almost invariably ran over buoy 14. This was true for both the 860-ft and the 950-ft ships, although the pilots used a smaller percentage of available maneuvering power for the smaller ship, which is evident based on comparison of maneuvering factor (Figures 117-124). The track plots for the proposed channel (Figures 72 and 75) demonstrate some improvement in this pattern; however, some collisions with buoy 14 did occur. Approximately the same amount of ship maneuvering power was used for the large ship in the proposed channel as in the existing channel. Visual analysis of the track-lines for all the channels indicates that the northeast wind seems to have actually helped the turning maneuver, with the composite ship tracks located farther to the south with the wind. Generally, the pilots stated that when they make the turn on a real ship, their focus of attention is on buoy 13a and they could not estimate their distance to buoy 14. However, actual collisions with buoy 14 have been rare, which indicates that the simulation results are exaggerated somewhat due possibly to perception difficulty affecting the timing of the turn.

42. Throughout the testing program, the outbound runs for all three channel designs were accomplished with good clearances between the ship and buoy 13a. The outbound runs for the alternative channel without wind (Figure 73) seem to follow the same pattern as the previous tests in the other channel designs; however, it turns out that only one of the pilots turned too

late and ran over buoy 14 for this set of conditions. All the rest of the pilots in the alternative channel without wind were able to steer clear of both sides of the channel through the turn. In the with-wind condition (Figure 76) the track-lines were very consistent: right down the center of the channel. Comparison of the maneuvering factor for the proposed and alternative channel runs in ebb tide (Figures 120, 121, 123, 124) indicates that approximately the same ship turning power was used in both channels. Although the track plots show that the pilots were more successful in the alternative channel, most of the widening on the inside of the turn does not appear to have been used directly by the pilots. However, it is clear that this widening had an effect on the pilots' ability to steer clear of buoy 14. Despite this, it is not considered necessary to widen the entire 100 ft near marker 13 and buoy 13a as was tested for the alternative design, but at least a 50-ft widening is advisable to allow room to transit slightly further south and away from buoy 14.

Pilot Questionnaire Response Analysis

43. To document the visiting pilots' thoughts concerning the simulation study and the channel design project in general, two different types of questionnaires were used. After each simulation, the pilot completed a test questionnaire to rate the run just completed for difficulty and realism. At the end of each visit, the pilot completed a final debriefing questionnaire to express his ideas and opinions of the channel project and simulator in general. The pilot ratings, carefully interpreted, can provide a general comparison of the navigability of the different channel designs and conditions.

Individual test questionnaire

44. For the first question on the run questionnaire, concerning run difficulty, the primary problem is that each pilot has his own idea of what is easy or difficult. Consequently, the results from questionnaire ratings on the 0 to 10 scale frequently possess a large amount of scatter between pilots. For example, one pilot may rate all the questions concerned with simple versus difficult in a 7 to 10 range while another may choose ratings in a 2 to 9 range. In a comparative analysis of different channel designs, information is lost during the process of averaging these ratings. Considering the pilot

ratings x_i as random variables, they can be standardized using the individual pilots' sample mean rating $\bar{x}$ and his sample rating standard deviation s_x. To accomplish this, all ratings chosen by each individual pilot on the scale of "very simple" to "very difficult" were algebraically added and analyzed for the sample mean and standard deviation. New standardized variables were then calculated for channel scenario comparison according to the following normal random variable relation,

$$X_i = \frac{x_i - \bar{x}}{s_x}$$

in which X_i are the standardized ratings of a particular pilot. Table 4 presents the results of this analysis for the question of run difficulty. Only the ratings for the runs conducted with the 950-ft ship are presented. A rating value of 0 indicates a mean (average) value. A large positive number indicates "very difficult" while a large negative number indicates "very simple."

Table 4

Pilot Ratings for Run Difficulty

Scenario from Table 1	Overall Difficulty of Run
7: existing, inbound, flood tide	0.2
13: proposed, inbound, flood tide	-0.2
20: alternative, inbound, flood tide	0.1
8: existing, inbound, flood tide, wind	1.2
14: proposed, inbound, flood tide, wind	1.0
21: alternative, inbound, flood tide, wind	0.9
9: existing, outbound, flood tide	-0.3
16: proposed, outbound, flood tide	-0.7
22: alternative, outbound, flood tide	-2.1
10: existing, outbound, flood tide, wind	-0.4
17: proposed, outbound, flood tide, wind	-0.4
23: alternative, outbound, flood tide, wind	-1.2
11: existing, outbound, ebb tide	0.1
18: proposed, outbound, ebb tide	-0.2
24: alternative, outbound, ebb tide	-1.5
12: existing, outbound, ebb tide, wind	0.8
19: proposed, outbound, ebb tide, wind	0.3
25: alternative, outbound, ebb tide, wind	-0.3

45. For the ratings presented in Table 4, the higher the algebraic value the greater was the perceived difficulty. It is evident that for the inbound runs the pilots did not perceive much difference in their performance in the three design channels. For the no-wind case, almost no difference in run difficulty can be seen for the channels. For the inbound, with-wind case the pilots rated the proposed and alternative channels as slightly less difficult than the existing channel. The overall level of difficulty was rated as significantly higher with wind than without wind. These results tend to support the earlier recommendation that even with a widened channel in place, some restrictions should be placed on the transits of these ships.

46. For the outbound runs the pilot ratings are decidedly more definitive. For all four sets of environmental conditions, the pilots rated the proposed and alternative channels as successively easier than the existing channel. The overall level of difficulty was higher for ebb tide conditions than for flood tide, and wind did not seem to be as critical for outbound as for inbound.

47. The remaining questions on the run questionnaire asked the pilots to rate the realism of the simulation model. These questions concerned such aspects as ship behavior, bank effects, wind effect, and currents. These ratings were not standardized as were the ratings for run difficulty because a by-channel comparative study of realism would not yield significant results; therefore, the realism ratings were retained in their original form. Generally, the pilots gave the simulator realism ratings of between 7 and 10. From comments collected on the questionnaires, the pilots' primary criticism of the use of simulation for channel design is the lack of a feel of "real danger" due to other ship traffic in the test channel. Whereas this may be the case, ship speed was considered critical for the study and served as the primary basis for channel design recommendations.

Final debriefing questionnaire

48. Results of the final questionnaire showed that the pilots generally preferred the 1,600-ft turning basin and the alternative design channel. A couple of the pilots suggested that the squared-off western end of the 1,600-ft turning basin be angled to allow more drift room during the turn. One pilot made the suggestion that the 42-ft-deep channel needs to be extended into the Main Channel to provide an escape route in the event an inbound ship

needs to abort the turn into Fishermans Channel. The pilots' comments from the four questions are as follows:

1. Which of the two proposed channel alignments in the Fisher Island Turning Basin area do you think is adequate?

Pilot C: "The 'WES alternative' is by far the best channel. The 'district proposal' would pose a very serious danger of hitting bottom at marker #2 [off the eastern tip of Lummus Island]. Bottoms would be torn open causing pollution."

Pilot D: "The only safe channel alignment here is to widen the area at 13a/14 and deepen at beacon #2-17. Any other alternative will not only needlessly endanger the ship in transit but also those at the various berths."

Pilot E: "The WES alternative is by far the best choice. The widening of the channel between buoys 13a and 14 greatly increases the ease and safety of turning into and out of the south channel [Fishermans Channel]. Under the district proposal the western edge of the Fisher Island T/B is too far to the east. Ships would ground on that edge near beacon #2. GUARANTEED!"

Pilot F: "The alignment which envisions dredging the entire basin as it is now shaped."

Pilot G: "The one with the widener @ 13[a] and 14 markers, so that the channel has almost 600 ft between those markers. The west end [of FITB] must be extended all the way to markers 2 and 17 [eastern tip of Lummus Island]."

2. Which of the new turning basin designs do you consider adequate based on past experience and on the simulator runs?

Pilot C: "The 1400' turning basin is inadequate. You would almost always have vessels docked there, possibly with an oil barge alongside, taking away maybe 125' from the T/B, and increasing risks. 1600' is absolute minimum. The smaller basin would also necessitate the use of more tugs, increasing costs."

Pilot D: "The 1600' turning basin is the only workable design. Various size ships will be at berths 74/76 [Dodge Island] with, at times, oil barges alongside, thus constricting the basin. This size would either eliminate altogether or reduce the number of tugs used."

Pilot E: "The 1400' turning basin is inadequate. There will almost certainly be ships berthed in this area constricting the amount of room available. The shape of the basin is almost as important as the size. Possible more study in this area?"

Pilot F: "The 1600' turning basin with some possible modifications."

Pilot G: "The one with the 1600 ft diameter but not with that N/S [north-south] cut at the west end. It's very advisable to make that cut with at least a 30 degree angle to the west due to the effect of the winds and currents. In my opinion currents will be stronger with the new channel & T/B."

Pilot H: - "1600 ft - extend lengthwise if possible."

3. What other modifications to the channel do you think are needed?

Pilot C: "The widening of Gov't cut at buoys 13a and 14 proved very useful in

making the turn into and out of F. I. [Fisher Island] T/B without scrapes. The widening at buoy #8 [entrance bend widener] would be useful to lesser draft vessels who would feel more effect of currents & wind than the deeply loaded vessels."

Pilot D: "The length of the two jetties should be identical to reduce the shearing effect of the currents. The widener in the outer bar cut [entrance bend] at buoys 6-6a should be enlarged. This would prevent the sterns of the larger ships from being too close to the bank while turning."

Pilot E: "Be sure to consider any work that may be necessary between the sea buoy and the entrance buoys. Our ships are really affected by the gulf stream currents in this area. With drafts in the 38-40 ft range you will need to take a close look at this section."

Pilot F: "Widening of Government Cut in the area of buoys 13a and 14. Also, widening outside of the jetties on the north side of the channel."

Pilot G: "The 42-ft channel must be continued to some extent into the north channel [Main Channel] west of marker 17. It will help on the effect of the currents while maneuvering in and out."

Pilot H: "Take out sharp turn at buoy #8 - widen. Take out sharp turn at markers 14/13[a] - widen to 600'."

4. Are there any modifications to the simulator which you feel would enhance our ability to conduct navigation studies?

Pilot C: "I cannot think of any modifications to your computer. I wish reality was as good."

Pilot D: "I was very satisfied with the program and felt that it was as realistic as possible... Lastly, thanks to all of you for allowing our input."

Pilot E: "Could improve on more realistic ship speeds and more side visuals. Great job - currents and winds were very realistic. Thanks for the opportunity to give our input..."

Pilot F: "Less sensitivity and smoother operation of the 'look-around' feature would be desirable."

Pilot G: "Include the squat effect. New large ships are using engines in the range of 50000 hp and the squat effect has to be considered."

Pilot H: - "Try a night simulation."

Ship-Ship Interaction

49. During ship transits through the FITB and into Fishermans Channel, the proximity of moored ships is a critical consideration for the pilots. Because of the hydrodynamic interaction between the docked and passing ships, mooring line tension could become critical if the moving ship is traveling too fast. The WES simulator has the capability of calculating the forces and moment on a moving vessel as a traffic ship passes; however, the present

investigation focuses on a stationary docked ship and the effect of a passing vessel on it. For the present application the interaction forces on the moored ship could not be computed during the real-time tests. Instead, a parametric investigation of the interaction forces was carried out as a post-process. The moored ship was assumed to be rigidly fixed for computation of forces and moments. The traffic ship was assumed to be moving on a parallel course past the moored ship at specified lateral distances from the stationary ship and at specified speeds. This process generated longitudinal and transverse interaction forces and moment on representative moored ships with ship speed and lateral separation distance as variables. These interaction forces cause ship motions, which in turn create actual mooring line tensions. The conversion of interaction forces into specific mooring line tensions is a complicated task which involves frequency-dependent oscillations of the moored ship and determination of the elasticity of the mooring system and thus is beyond the scope of the present study.

50. Figures 141-164 show the results of interaction calculations for two ship speeds and four lateral separation distances. The moments and forces are plotted against the longitudinal separation distance. Two ship combinations were tested to cover a range of possible interaction situations in the FITB. These cases were with the design Econoclass containership (950 ft x 106 ft x 38 ft) passing both an identical moored containership and a docked oil tanker. The 78,000-deadweight-ton (78 kdwt) oil tanker was 784 ft long and 122 ft wide and had a draft of 40 ft. The tests were run assuming parallel courses with the moored ship heading in the same direction (passing) as well as with the moored ship heading in the opposite direction (meeting). With the interaction formulation used, the longitudinal and lateral forces are the same regardless of the heading of the moored ship; however, because of the fore-aft asymmetry of the ship's hull the moment is different. These tests were designed to represent the actual case of a tanker moored at the Fisher Island petroleum dock and a large containership moored at the Lummus Island container terminal while a containership enters Fishermans Channel. The traffic ship had constant speeds of 5 and 10 knots and lateral separation distances from the stationary ship (center line to center line) ranging from the hulls nearly touching each other to 400 ft apart. The case in which the two hulls nearly touched was not intended to represent a possible real situation but is shown to establish limiting values. Furthermore, it is not likely that a ship will

enter the FITB at a speed of 10 knots; however, these results also provided a limiting range of possibilities. By observing the mean speed and lateral separation distances derived from the simulation test runs at the location of the tanker moored at Fisher Island and the containership moored at Lummus Island, a relative measure of the forces and moments acting on the moored ships can be obtained. In the proposed channel, the mean ship speed was approximately 5.2 knots while in the alternative channel the mean speed was about 4.9 knots when passing the moored tanker. Also, the mean lateral separation was 200-250 ft to the tanker and 100-150 ft to the containership. Therefore, the center-line lateral separation distance was about 300-350 ft to the tanker and 200-250 ft to the containership. Thus for the most critical case (passing the moored containership) at a passing speed of about 5 knots, the moments are less than 50,000 ft-tons and the lateral and longitudinal forces are less than 250 tons and 30 tons, respectively.

51. A literature search uncovered two applicable studies conducted concerning mooring line tensions caused by ship interactions. In one study (Remery 1974), the investigator conducted scale physical model tests of a deep-draft ship passing a moored vessel. This study involved measurement of forces and moments on the hull of a fixed vessel as well as measurement and calculation of mooring system forces based on a simplified linear spring model. For the calculation of the interaction hull forces and moments, a series of tests were conducted (Remery 1974) with ship models similar in geometry to the design vessels in the Miami Harbor simulation study. The test series was conducted with a 100,000-deadweight-ton (100 kdwt) moored tanker being passed by tankers of three different sizes (30, 110, and 160 kdwt) on a parallel course traveling at speeds of 4.0, 5.5 and 7.0 knots and at varying lateral separation distances. The referenced study concluded that the interaction forces were proportional to the square of the speed of the passing vessel. The test condition from this study that was most similar to that in the Miami simulation study was the 100-kdwt moored vessel being passed by the 110-kdwt ship with a lateral separation distance of approximately 100 ft skin to skin. This condition is similar to the Miami study test in which a moored 950-ft containership was passed by an identical vessel with both facing the same direction. Although the containership in the Miami study was lighter (73 kdwt) than the tanker in Remery (1974), the New York class containership hull form is similar to that of a tanker, and the following tabulation shows

Forces and Moments	Remery (1974)	Miami Study
Longitudinal force, long tons	58	30
Lateral force, long tons	288	250
Moment, ft-long tons	42,900	50,000

fairly close agreement between the two sets of results. The results shown are peak values for the test case of a passing ship speed of 5.0 knots and a lateral separation distance of 100 ft skin to skin (approximately 200 ft center line to center line). The Miami results are the same as discussed in the preceding paragraph and are taken from Figures 141-143. As would be expected, the vessel interaction tested in Remery (1974) is stronger than for the smaller vessels in the Miami study, except in the case of the moment. This is probably due to the extra length of the containership (950 ft) over that of the tanker (843 ft) in Remery (1974), indicating a larger moment arm. These results indicate that the analytical method used in the Miami study produces hull forces and moments with an order-of-magnitude agreement with physical model measurements.

52. Remery (1974) also measured mooring forces (forces on a mooring system resulting from the response of the moored ship to the interaction forces) during vessel passing situations through use of a linearly flexible spring of known force constant. This simplified model was designed to substitute for an actual mooring system made up of a complicated array of lines with nonlinear elasticity and different sizes and materials. The physical model tests run for this investigation involved a 100-kdwt moored tanker being passed by a 160-kdwt tanker, on a parallel course, moving at a speed of 7 knots at a lateral separation distance of 100 ft skin to skin. For the case just mentioned, Remery (1974) shows that the maximum lateral mooring force for a linear spring system with a force constant of 50 tons/ft is approximately twice the maximum lateral hull interaction force. In other words, the dynamics of vessel motion resulted in an amplification of the interaction forces on the mooring system due to added acceleration components. If the rough amplification factor of two is applied to the 250-ton hull lateral force for the containership case in the Miami study (see tabulation in preceding paragraph), an approximation of the maximum lateral mooring force is 500 tons. The moment was not measured separately in Remery (1974); however, since the ship model was free to respond to the passing ship, the force measured was the

true amount required to restrain the ship and included the effect of the interaction moment. In a real mooring system, lateral forces would be resisted primarily by the breast lines. The longitudinal mooring force, resisted by the spring lines in a real system, was not discussed in Remery (1974); however, generally, these results suggest that it is approximately 10-20 percent of the lateral force magnitude. It should be stressed that this is a very simplified model, with known spring constant, of a complex dynamic process and the results constitute only a first-time order of magnitude approximation.

53. Another study (Computer Aided Operations Research Facility (CAORF) 1987) investigated mooring forces in Oakland Harbor, California, via analytical methods, and included test scenarios similar to those in Miami. In the Oakland Harbor study, a moored SL18 containership was passed by a 950-ft Econoclass containership on a parallel course. The SL18 containership had a length of 720 ft, a beam of 95 ft, and a draft of 30 ft while the Econoclass ship was the same vessel as in the Miami study except with a draft of 36 ft. Figure 165 shows the orthogonal mooring forces, from the Oakland study, as a function of ship speed. The lateral separation distance for this test was 250 ft center line to center line. This plot indicates that the lateral mooring force for a 5-knot passing speed is about 120 tons and the longitudinal mooring force is about 30 tons. The peak longitudinal interaction force of 30 tons from the Miami study is the same magnitude as the longitudinal mooring force from the Oakland study. However, the lateral interaction force of 250 tons (estimated maximum lateral mooring force of 500 tons) in the Miami study is significantly different from the lateral mooring force of 120 tons from the Oakland study. It is not possible to draw a direct comparison between the results from the Oakland study and those from the Miami study because actual mooring forces are not available in the Miami case. Additional factors contributing to magnitude differences are a larger moored ship and smaller lateral separation distance in the Miami study (200 ft versus 250 ft). As a further note, the forces from the Oakland study represent total lateral and longitudinal mooring forces and should not be interpreted as tensions in particular mooring lines. The primary conclusion from this comparison is that there is an order-of-magnitude agreement between results of the two studies.

54. Of the two related studies presented, the results from Remery (1974) are considered more significant and helpful because they are based on measured

physical model results and not analytical computations. The significant result from these computations is that in both the proposed and alternative plan channels the traffic ship had similar lateral separation distances to the moored ships. However, the runs in the alternative channel had slightly lower traffic ship speeds than those in the proposed channel. Based on this and noting that the forces and moments are a function of the square of the ship speed, the alternative channel will result in reduced mooring ship forces and moments and mooring line forces.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

55. Figures 166 and 167 show the details of the Miami Harbor channel design recommendations based on simulation results and discussions with the Jacksonville District and the professional pilots and considering limitations to further modification that might improve navigation, e.g., widening the Fishermans Channel to 500 ft. The following specific recommendations are made:

- a. A 150-ft widening on the north side of the entrance channel bend seaward of the jetties is recommended to allow the pilots a better setup for the cross currents at the jetty entrance. This area must be properly maintained to the full project depth to be useful.
- b. At the eastern end of the FITB in the vicinity of buoys 13a and 14, widening is recommended for both sides of the channel. A 100-ft widening is recommended on the north side and a 50-ft widening on the south side in the vicinity of buoy 13a (Figure 167a). Eliminating the point would eliminate the need for buoy 13a, giving the pilots a significant increase in maneuvering space on the inside of the turn.
- c. The deepening project should extend over the entire existing area of the FITB including the portion near the eastern end of Lummus Island. The proposed channel did not have this area deepened and the design proved to be inadequate for the turn into Fishermans Channel. Other design considerations which support this recommendation for the FITB include the continued use of the basin for turning of smaller ships and the difficulty of marking deep water in such a high traffic area.
- d. The recommended configuration (Figure 167b) for the new turning basin in Fishermans Channel is similar to that tested in the District-proposed channel with an additional modification to the alignment at the western end.

56. In addition to these recommendations, the following are specific conclusions based on these simulation tests which could be significant for future shipping operations in Miami Harbor:

- a. The simulations did not address the need for an emergency lane extending into the Main Channel to be used by inbound ships if circumstances require the pilot to abort the turn into Fishermans Channel. If this plan were to be implemented, the 42-ft proposed channel depth would need to be extended approximately two to three ship lengths (2,000 to 3,000 ft) into Main Channel. Additional simulations could assist in defining more specifically the additional length and width required.
- b. It was evident from the inbound simulations that even with the recommended channel, extreme caution is required to bring large containerships into Fishermans Channel. Times of strong flood

tide and wind should be avoided if at all possible. Some transit time restrictions will probably be required once Fishermans Channel is deepened and the new turning basin is constructed if no emergency channel is provided as discussed.

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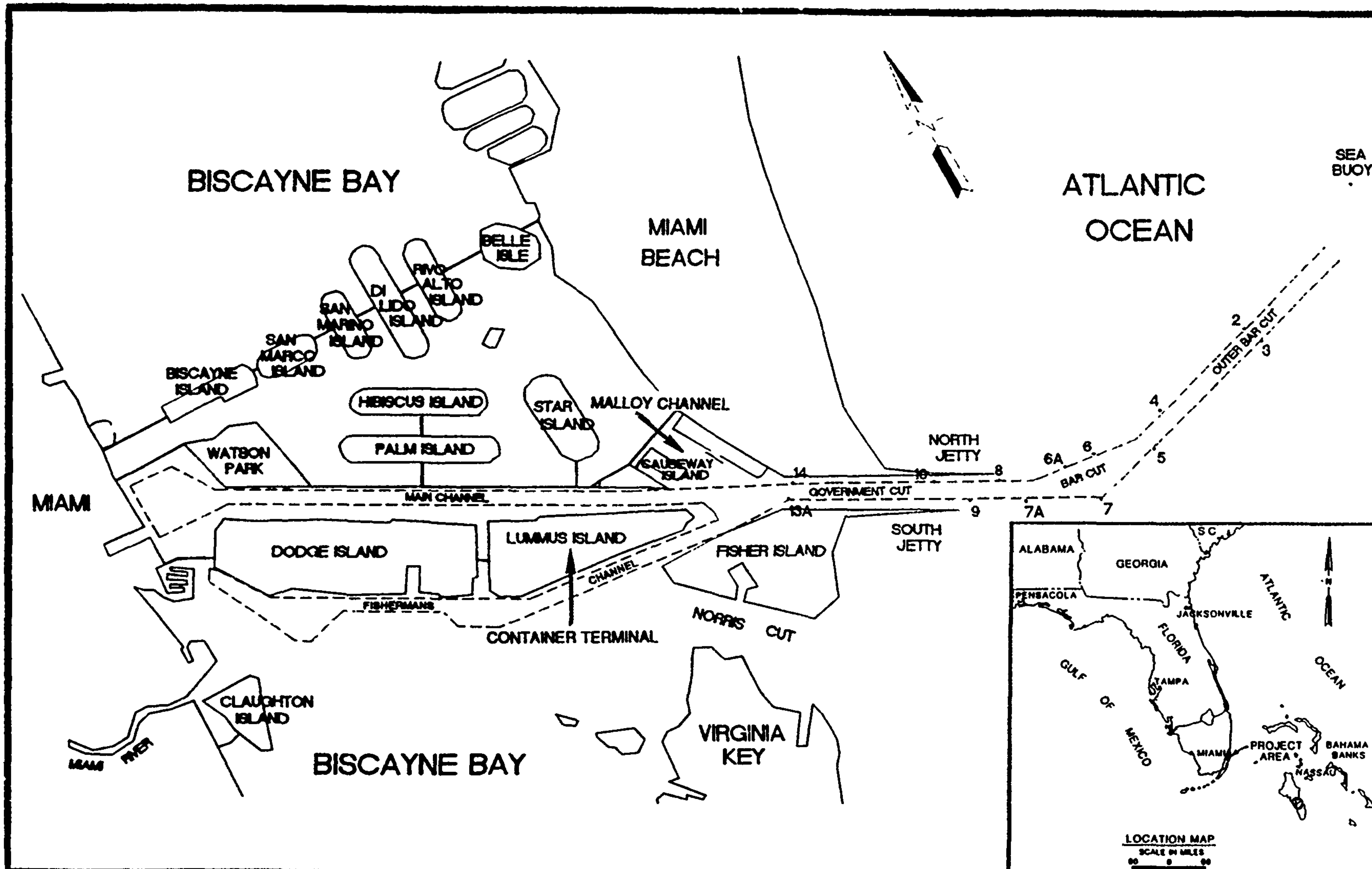


Figure 1. Miami Harbor study area

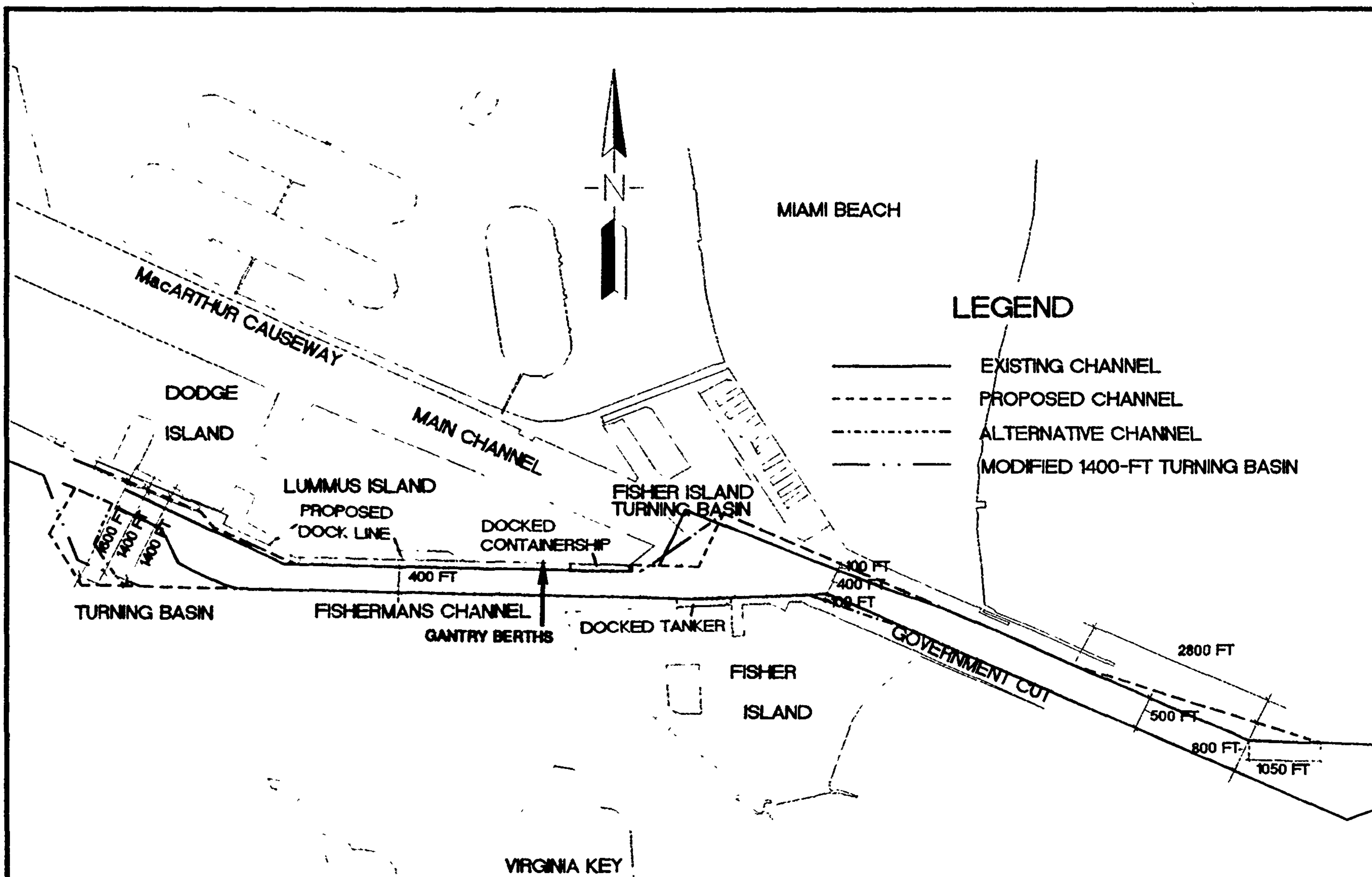


Figure 2. Simulator test channels

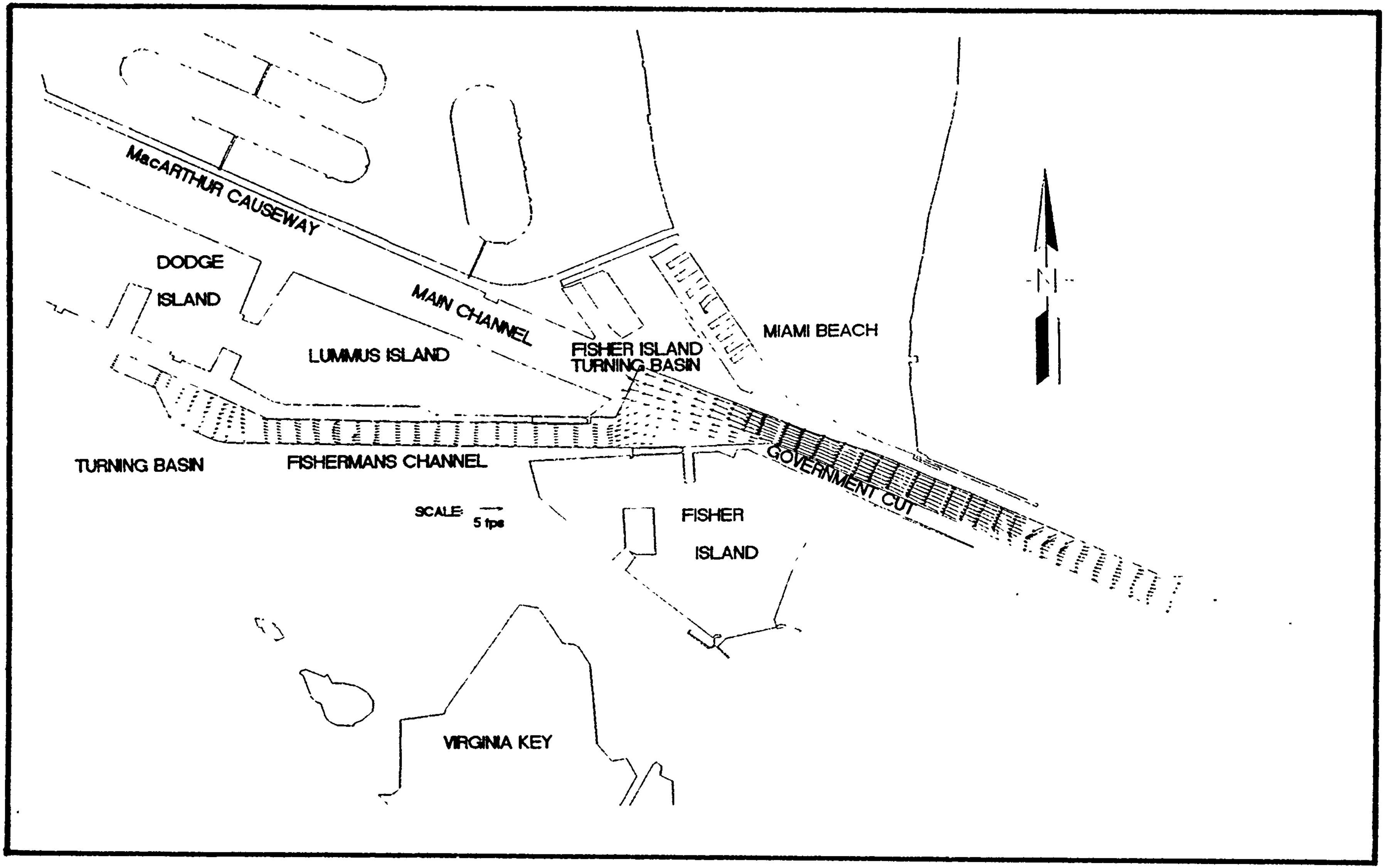


Figure 3. Maximum spring flood tide, northeasterly wind

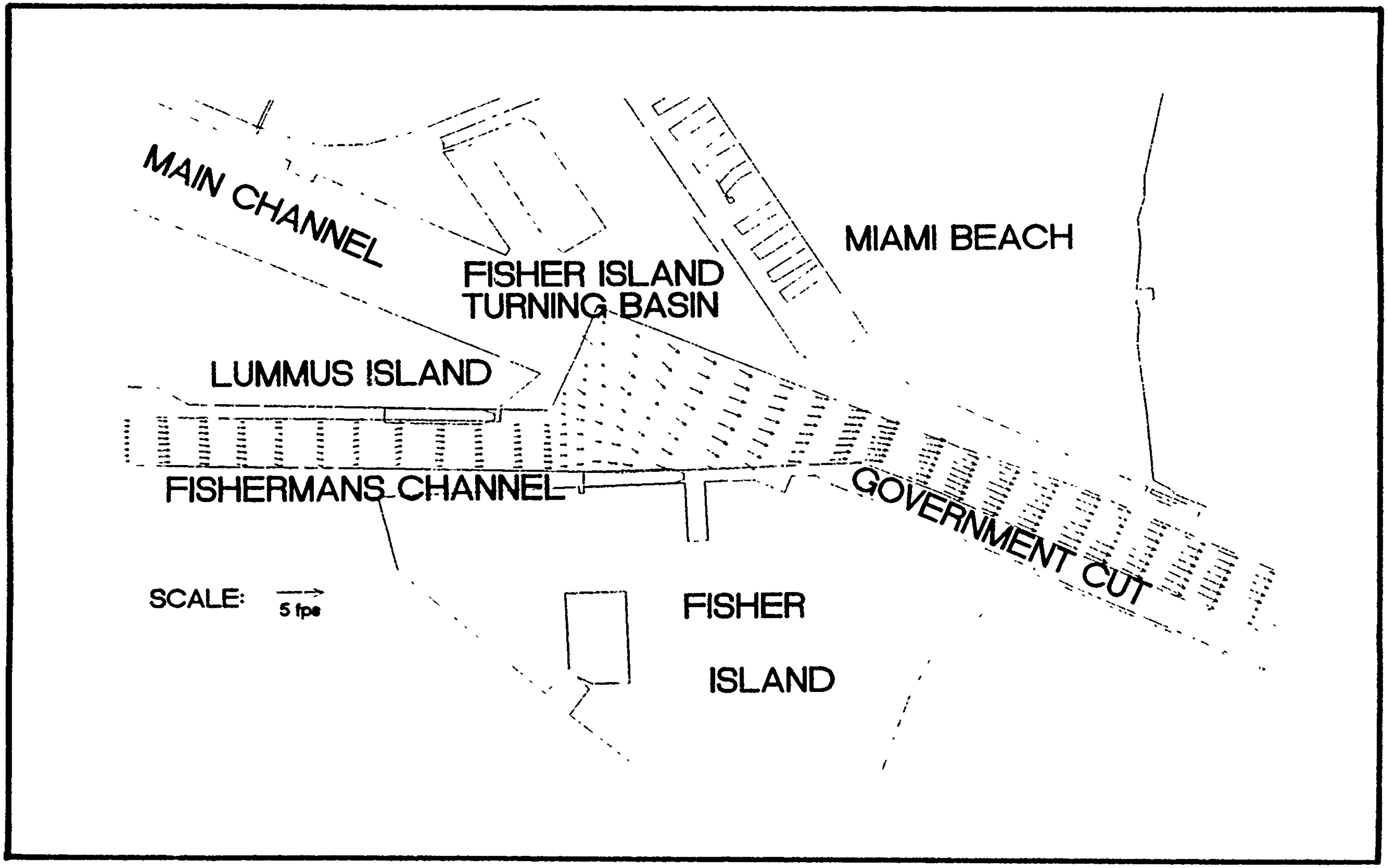


Figure 4. Maximum spring ebb tide, Fisher Island turning basin

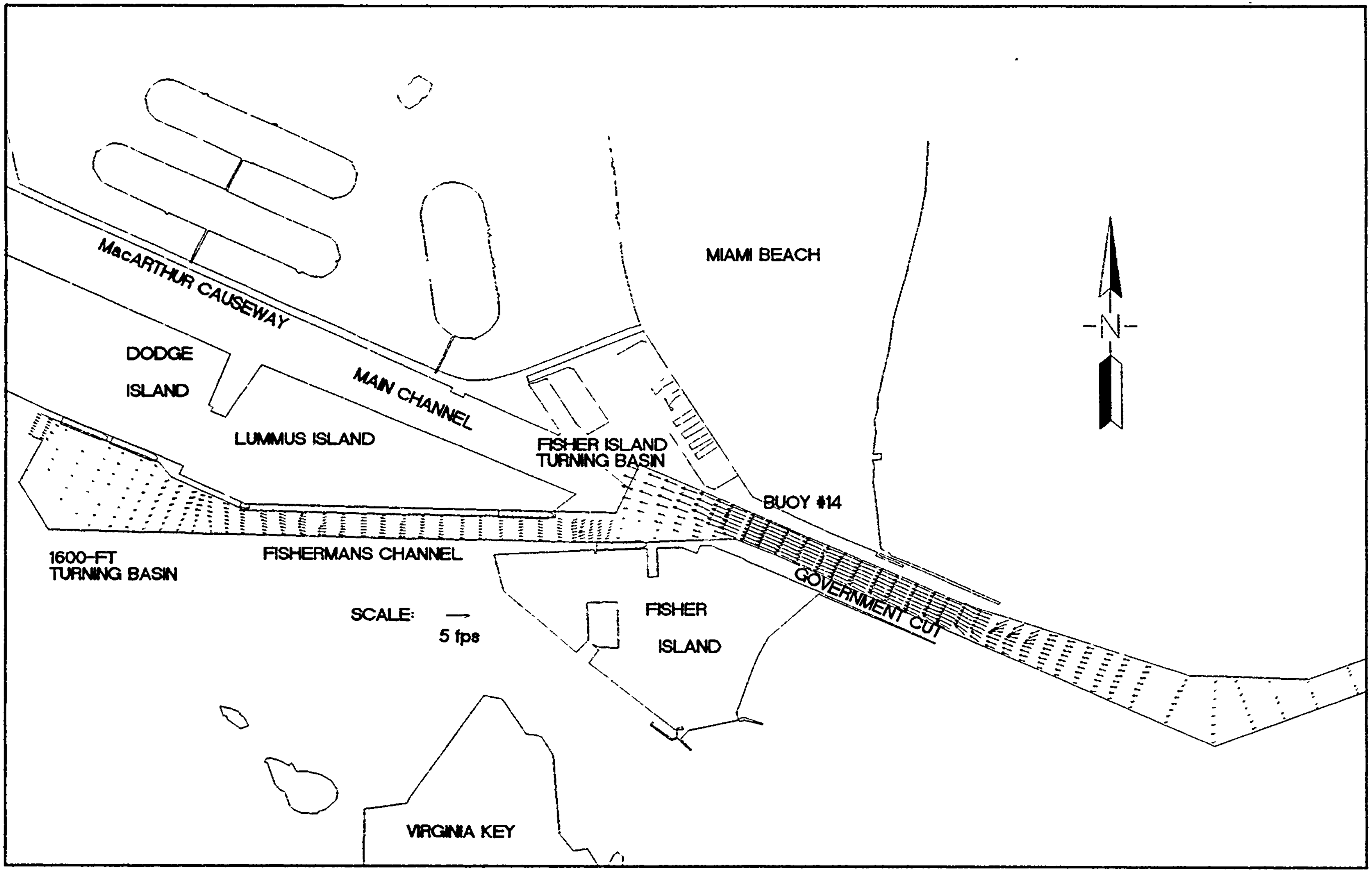


Figure 5. Maximum spring flood tide, proposed channel

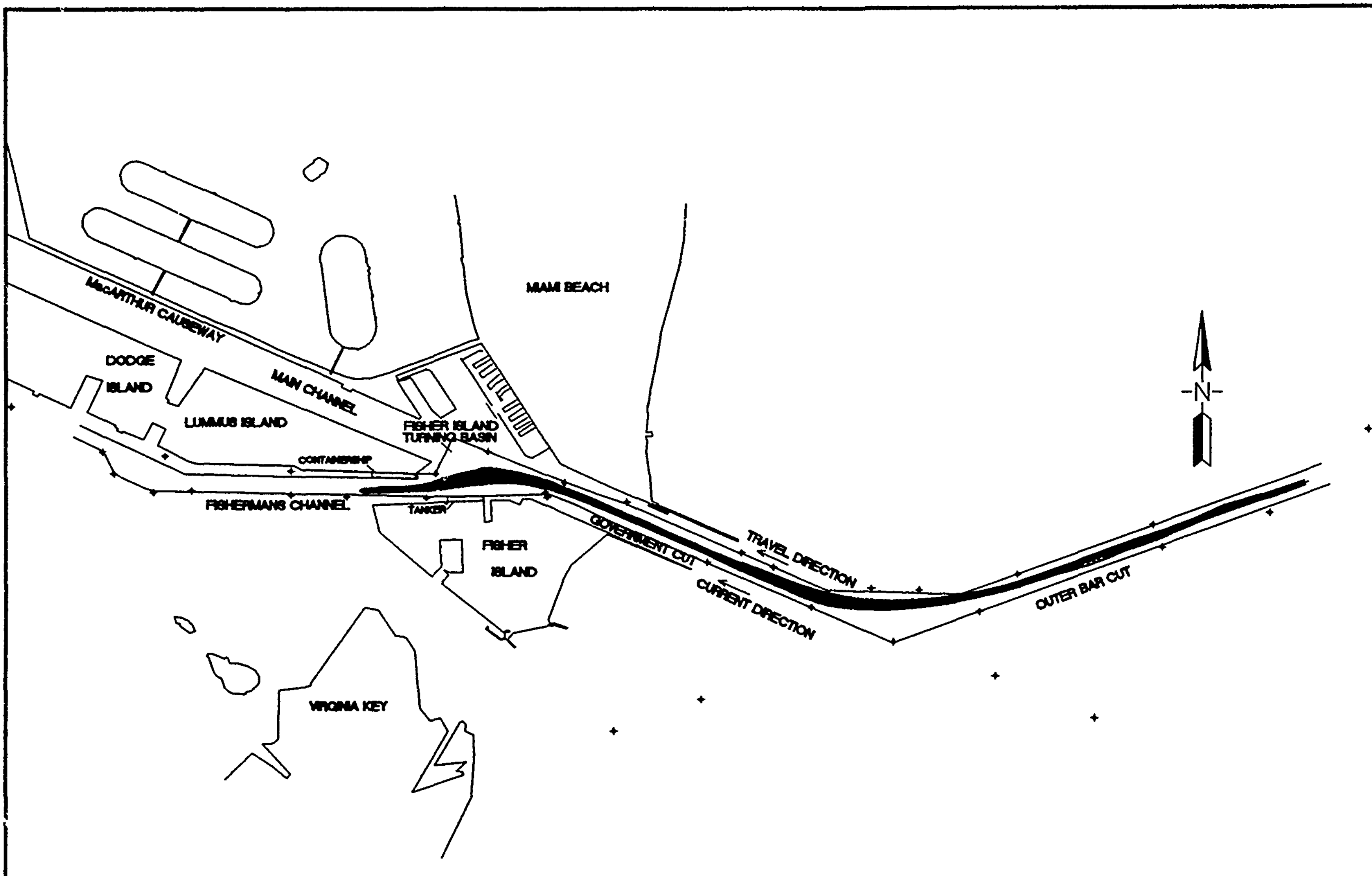


Figure 6. Composite track plots, existing channel, 860-ft containership, 34-ft draft, flood tide, inbound, all runs

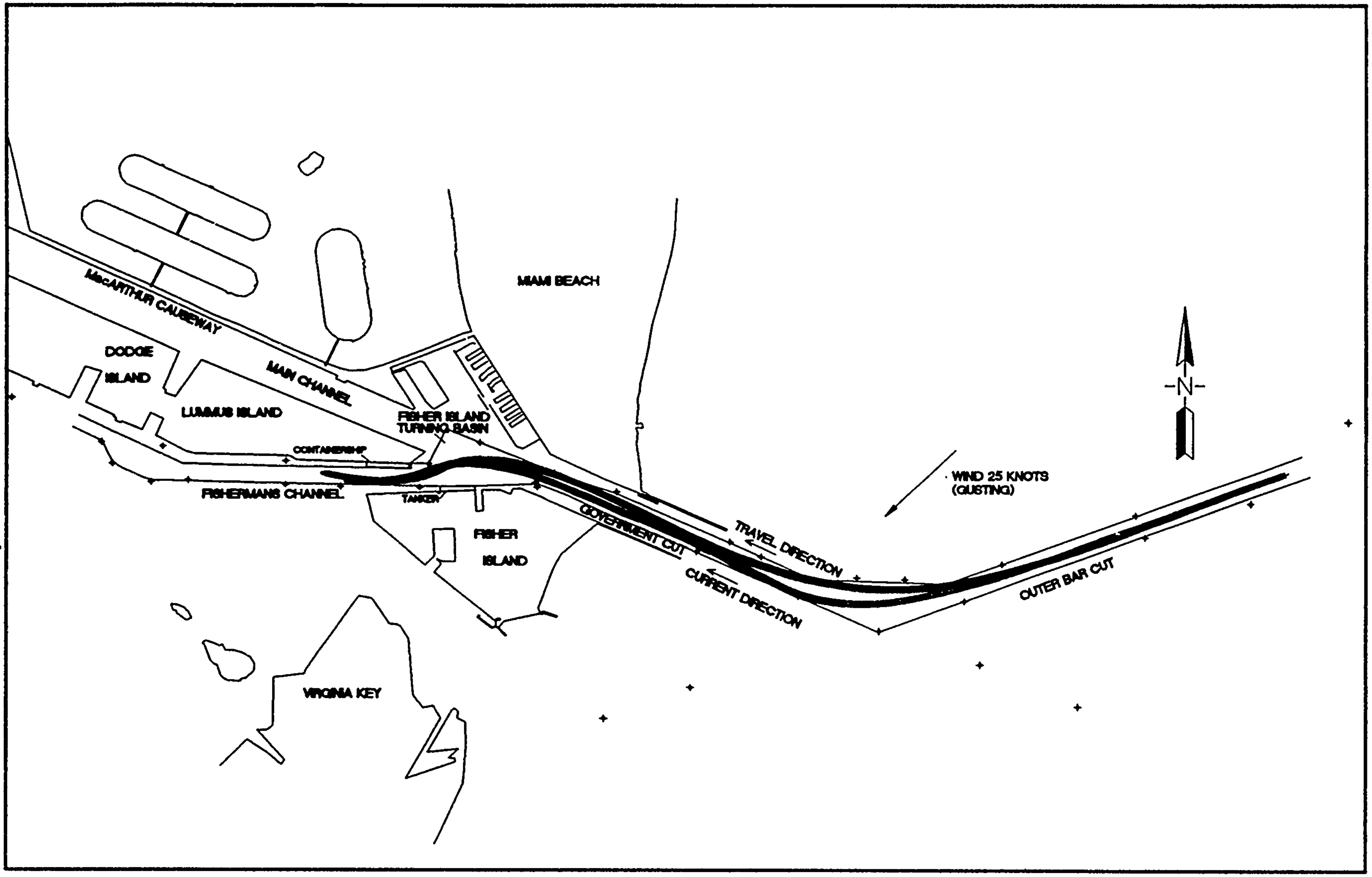


Figure 7. Composite track plots, existing channel, 860-ft containership, 34-ft draft, flood tide, 25-knot northeast wind, inbound, all runs

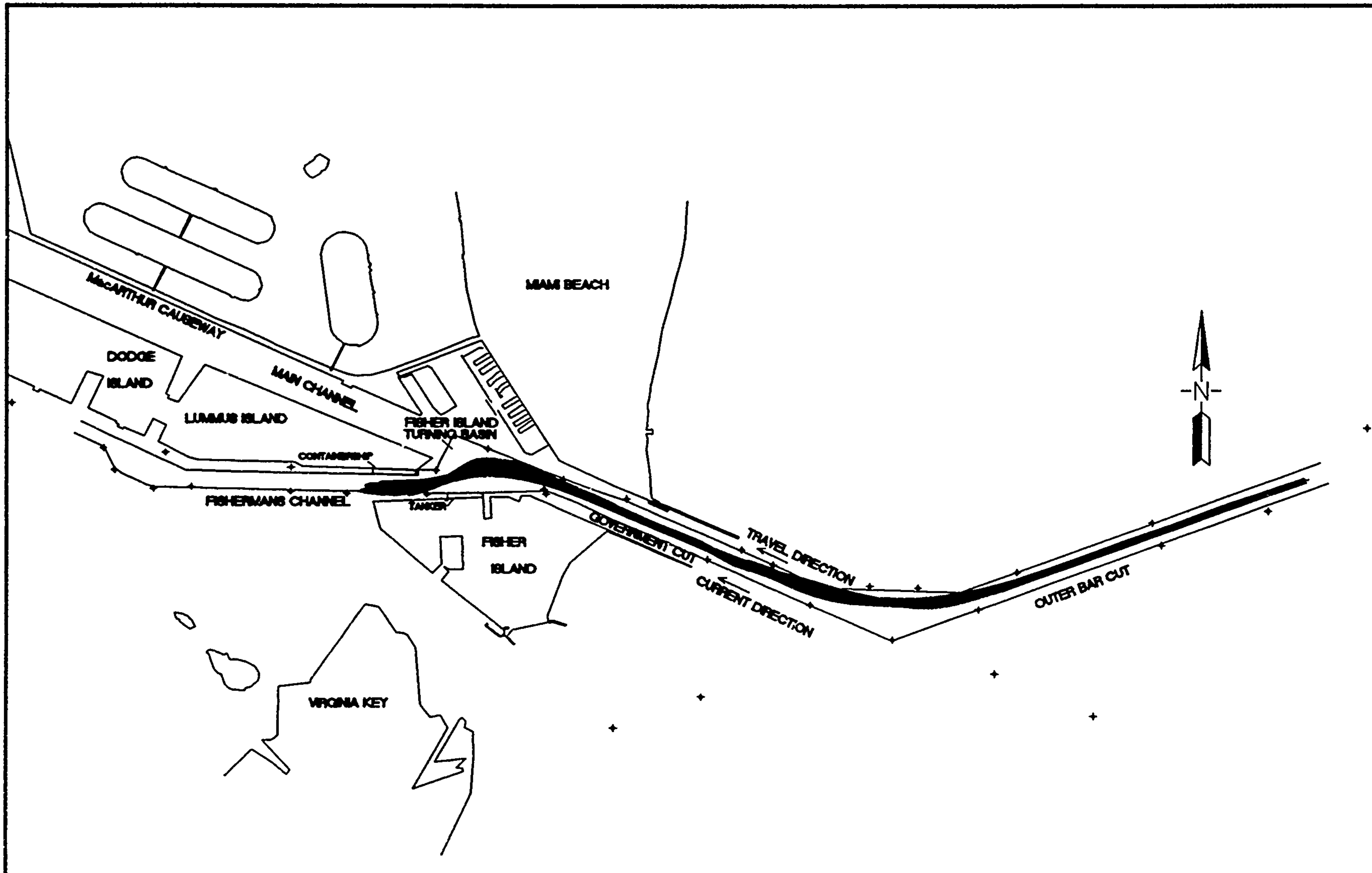


Figure 8. Composite track plots, existing channel, 950-ft containership, 34-ft draft, flood tide, inbound, all runs

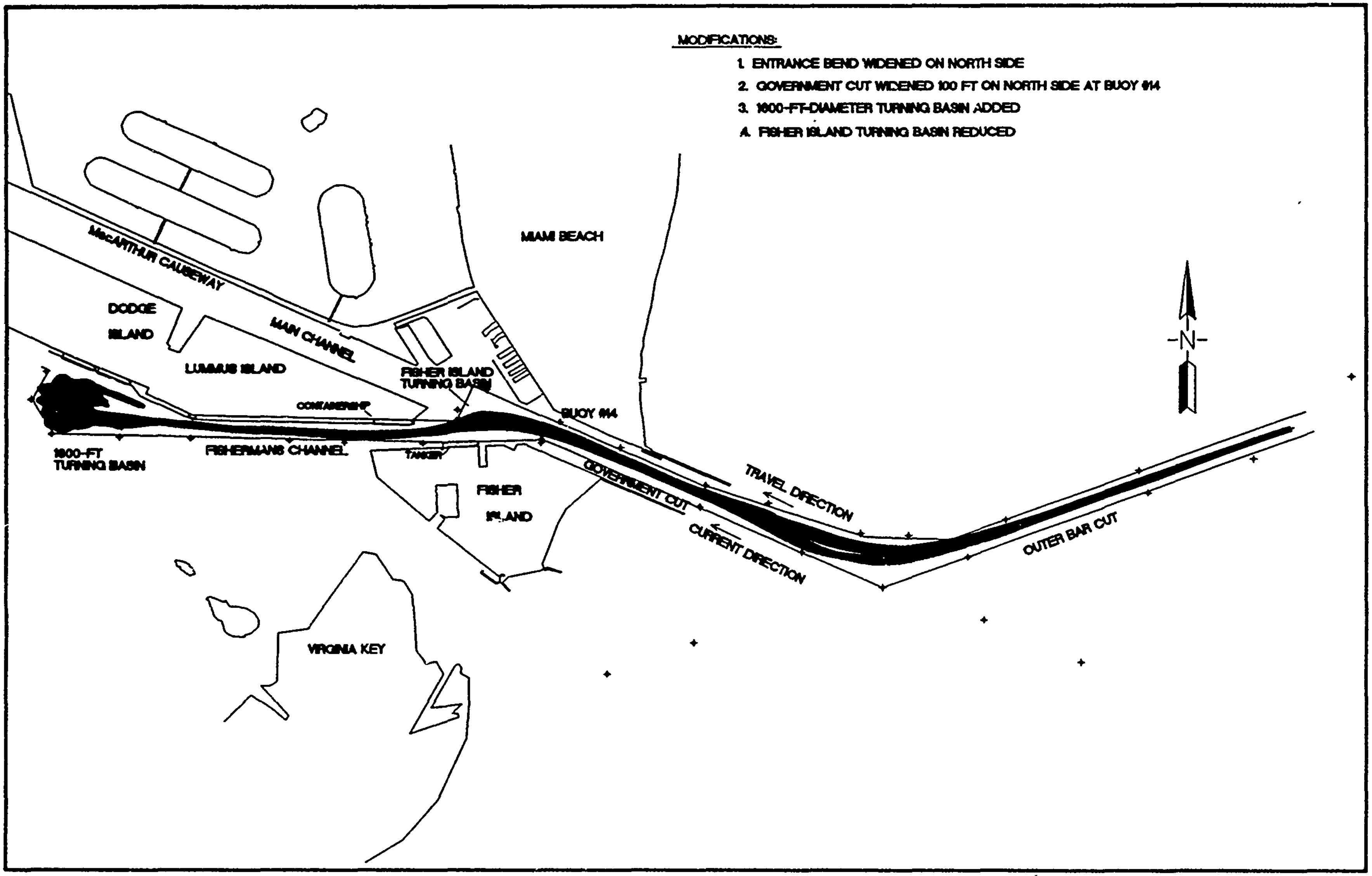


Figure 9. Composite track plots, proposed channel, 950-ft containership, 38-ft draft, flood tide, inbound with tugs, all runs

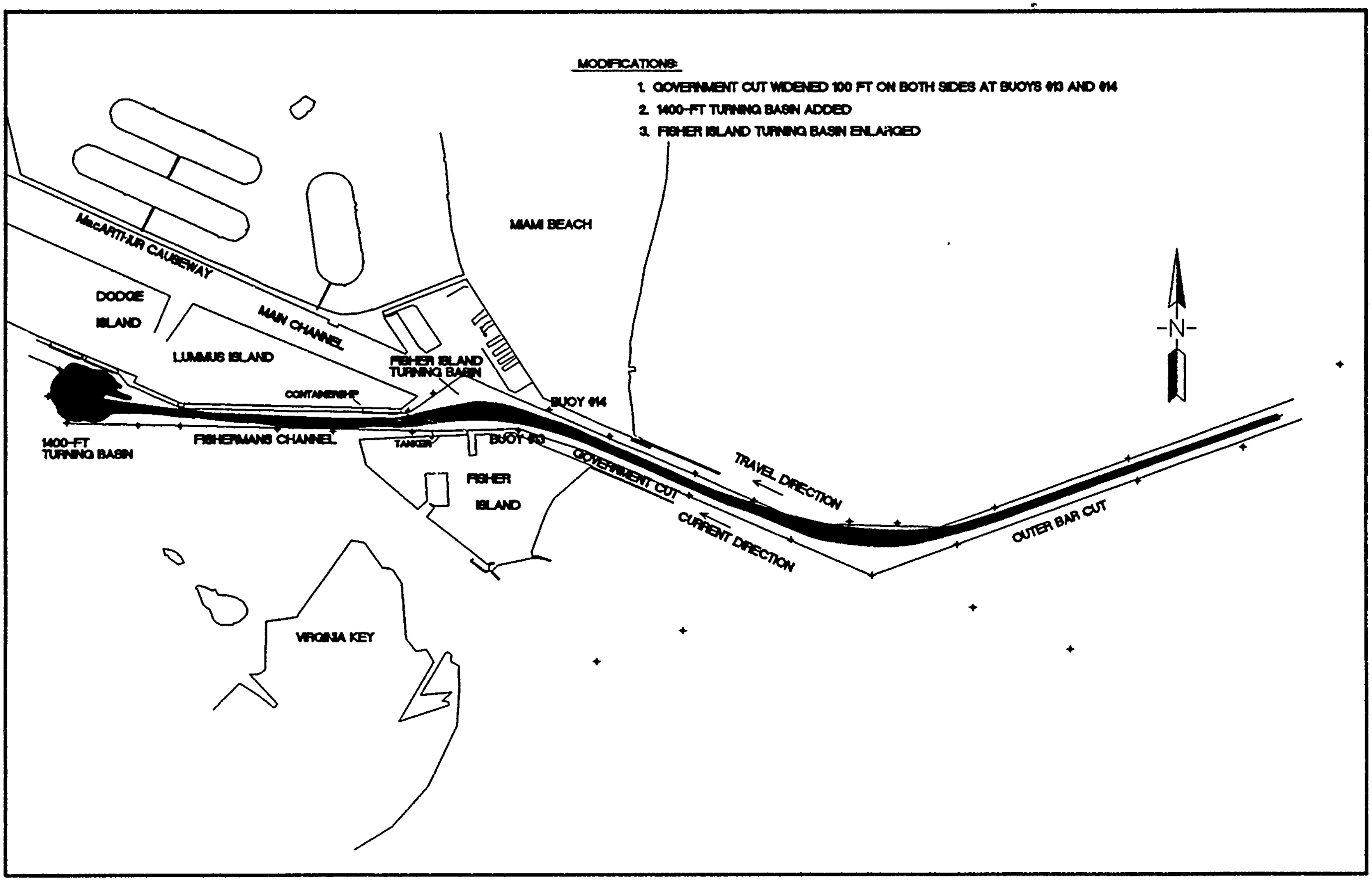


Figure 10. Composite track plots, alternative channel, 950-ft containership, 38-ft draft, flood tide, inbound with tugs, all runs

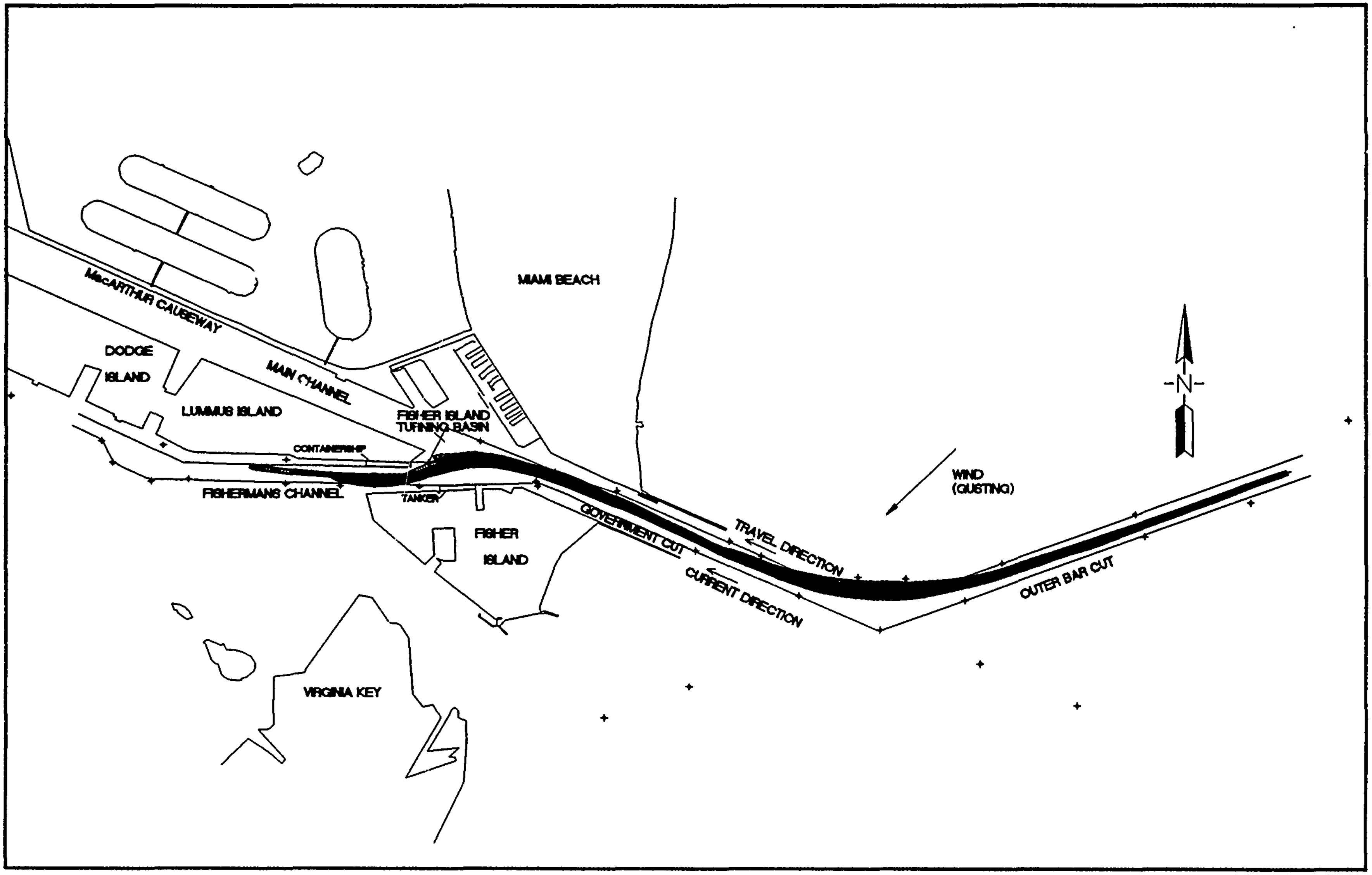


Figure 11. Composite track plots, existing channel, 950-ft containership, 34-ft draft, flood tide, with wind, inbound, all runs

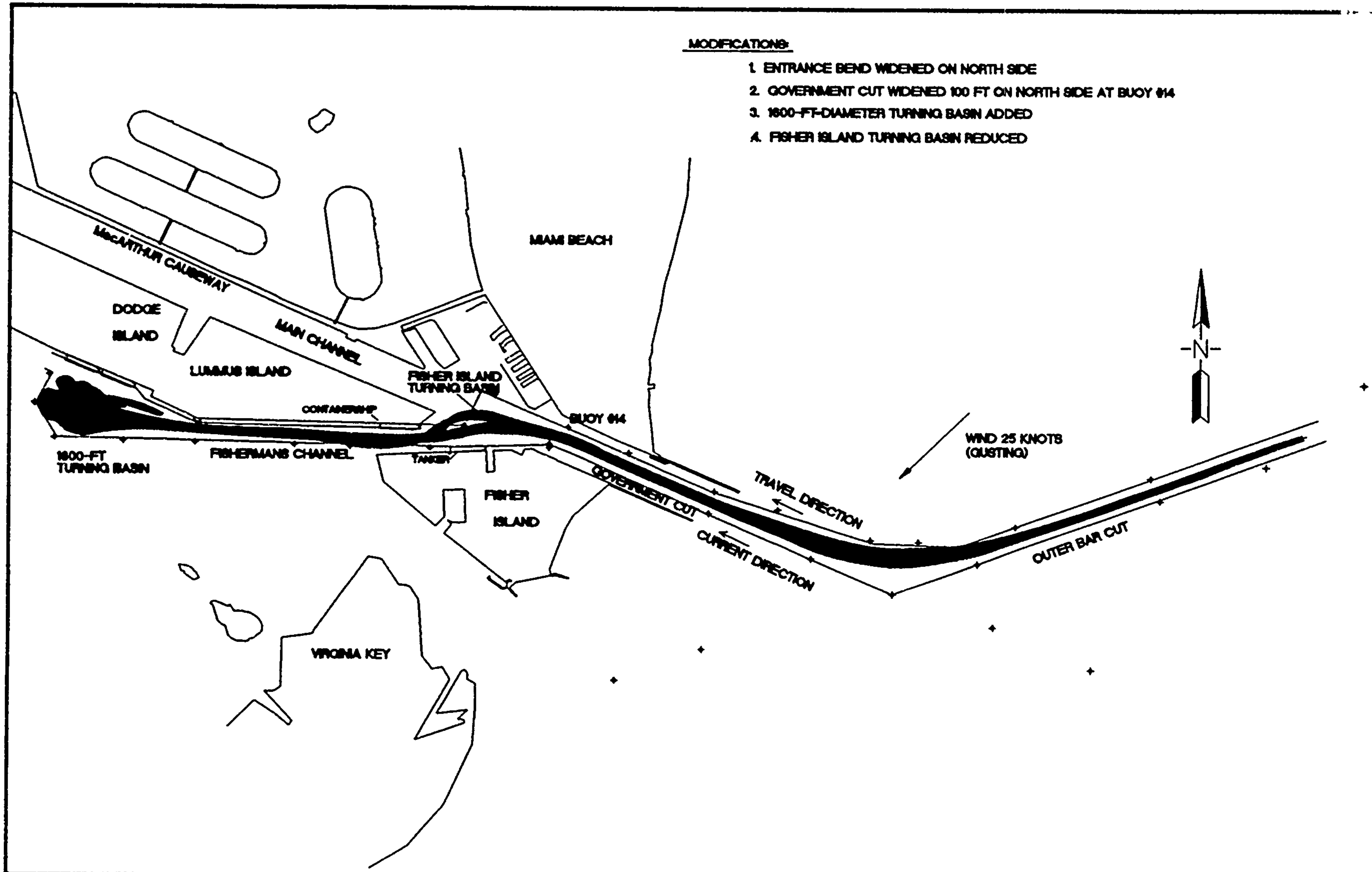


Figure 12. Composite track plots, proposed channel, 950-ft containership, 38-ft draft, flood tide, 25-knot northeast wind, inbound with tugs, all runs

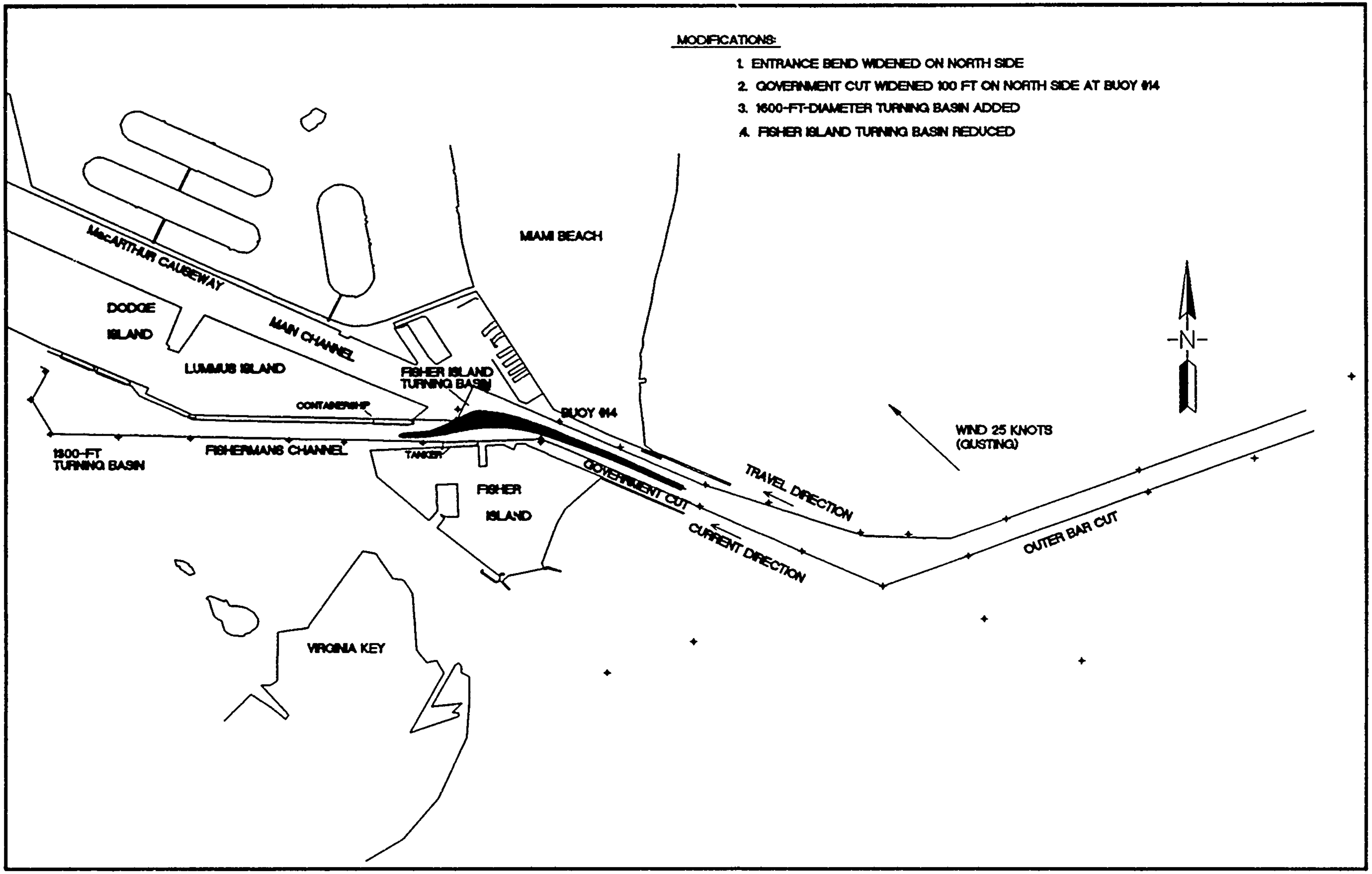


Figure 13. Composite track plots, proposed channel, 950-ft containership, 38-ft draft, flood tide, 25-knot southeast wind, inbound, all runs

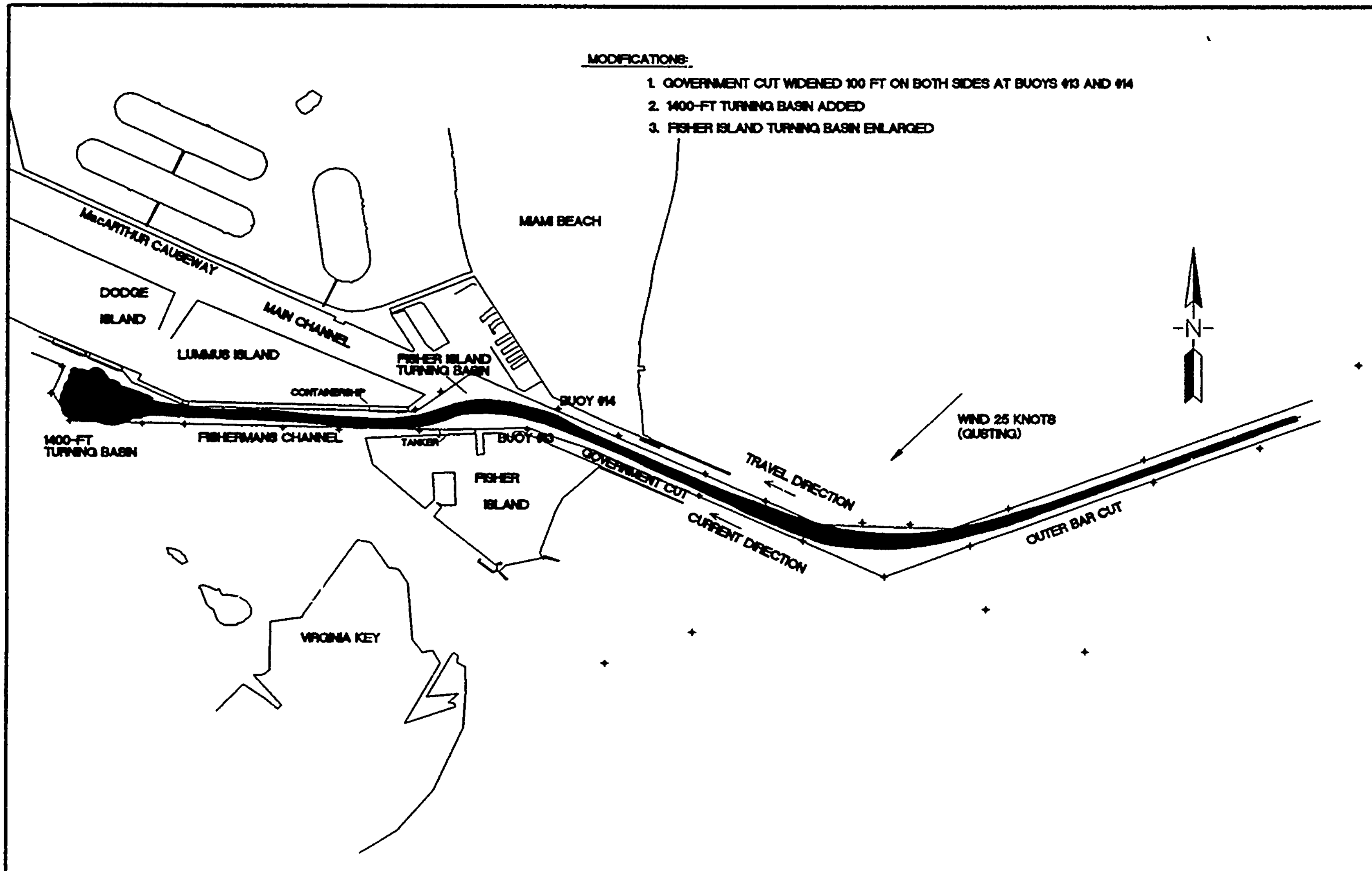


Figure 14. Composite track plots, alternative channel, 950-ft containership, 38-ft draft, flood tide, 25-knot northeast wind, inbound with tugs, all runs

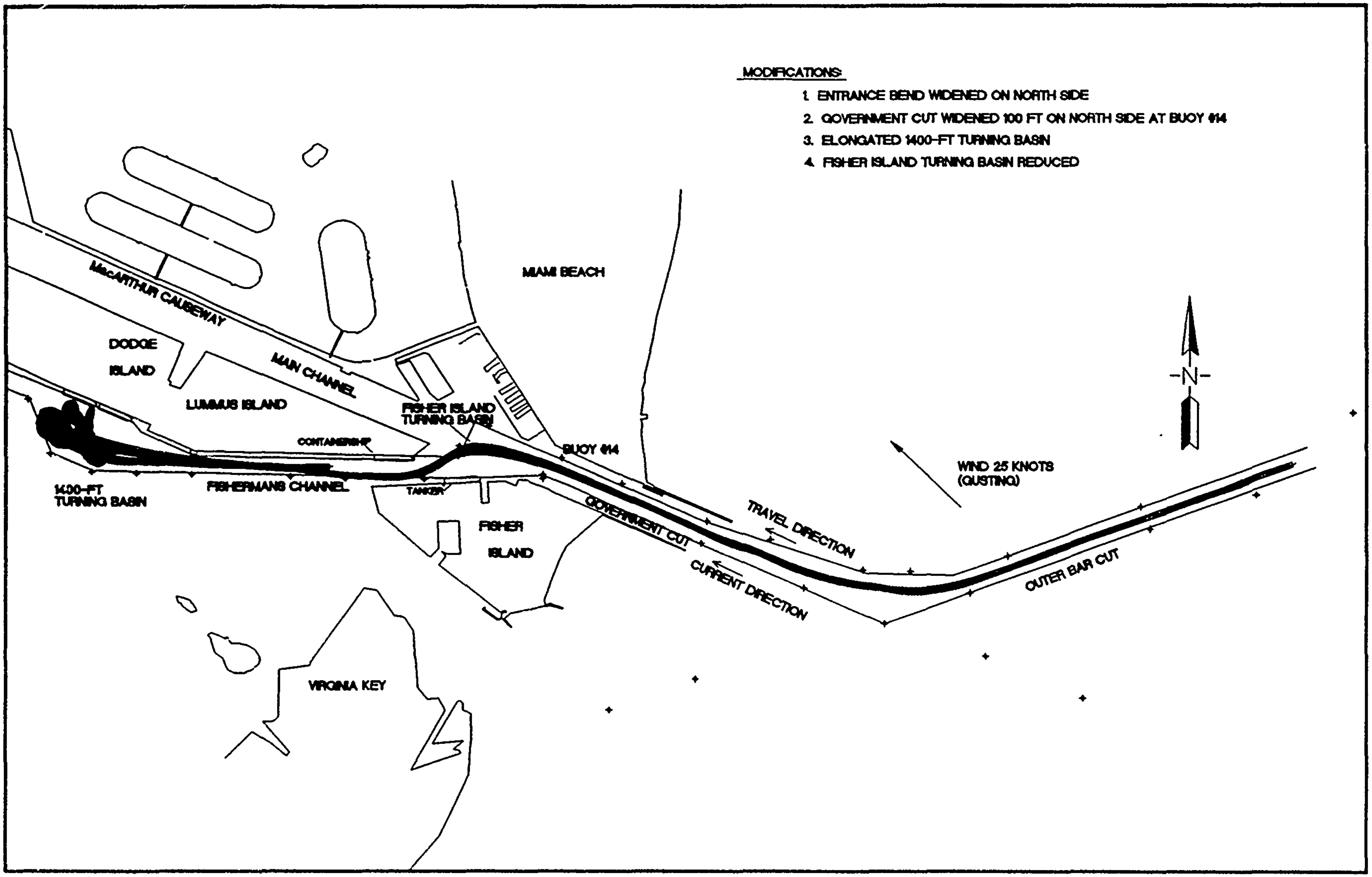


Figure 15. Composite track plots, modified 1,400-ft turning basin, 950-ft containership, 38-ft draft, flood tide, 25-knot southeast wind, inbound with tugs, all runs

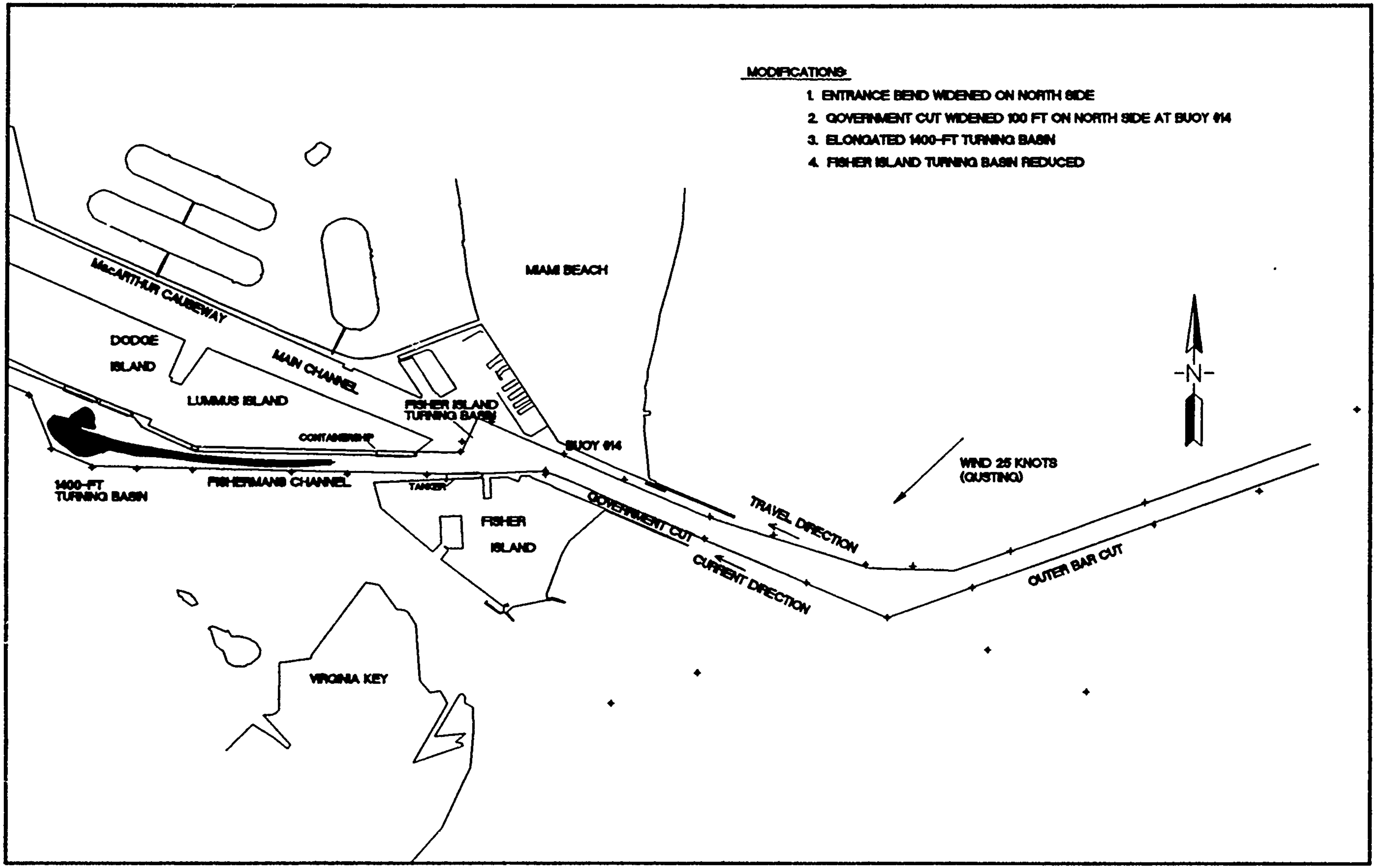


Figure 16. Composite track plots, modified 1,400-ft turning basin, 950-ft containership, 38-ft draft, flood tide, 25-knot northeast wind, inbound with tugs, pilot H

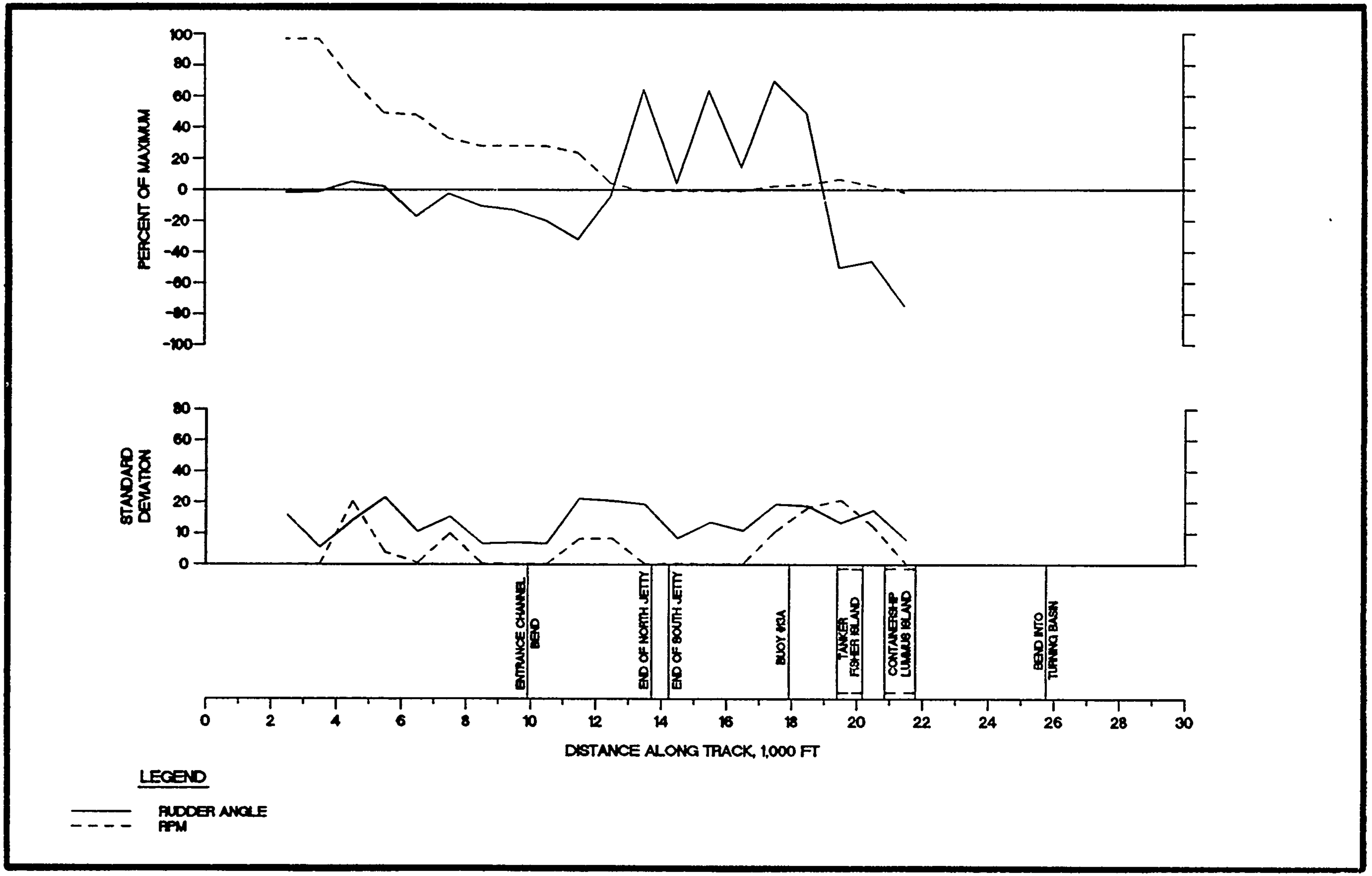


Figure 17. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot C

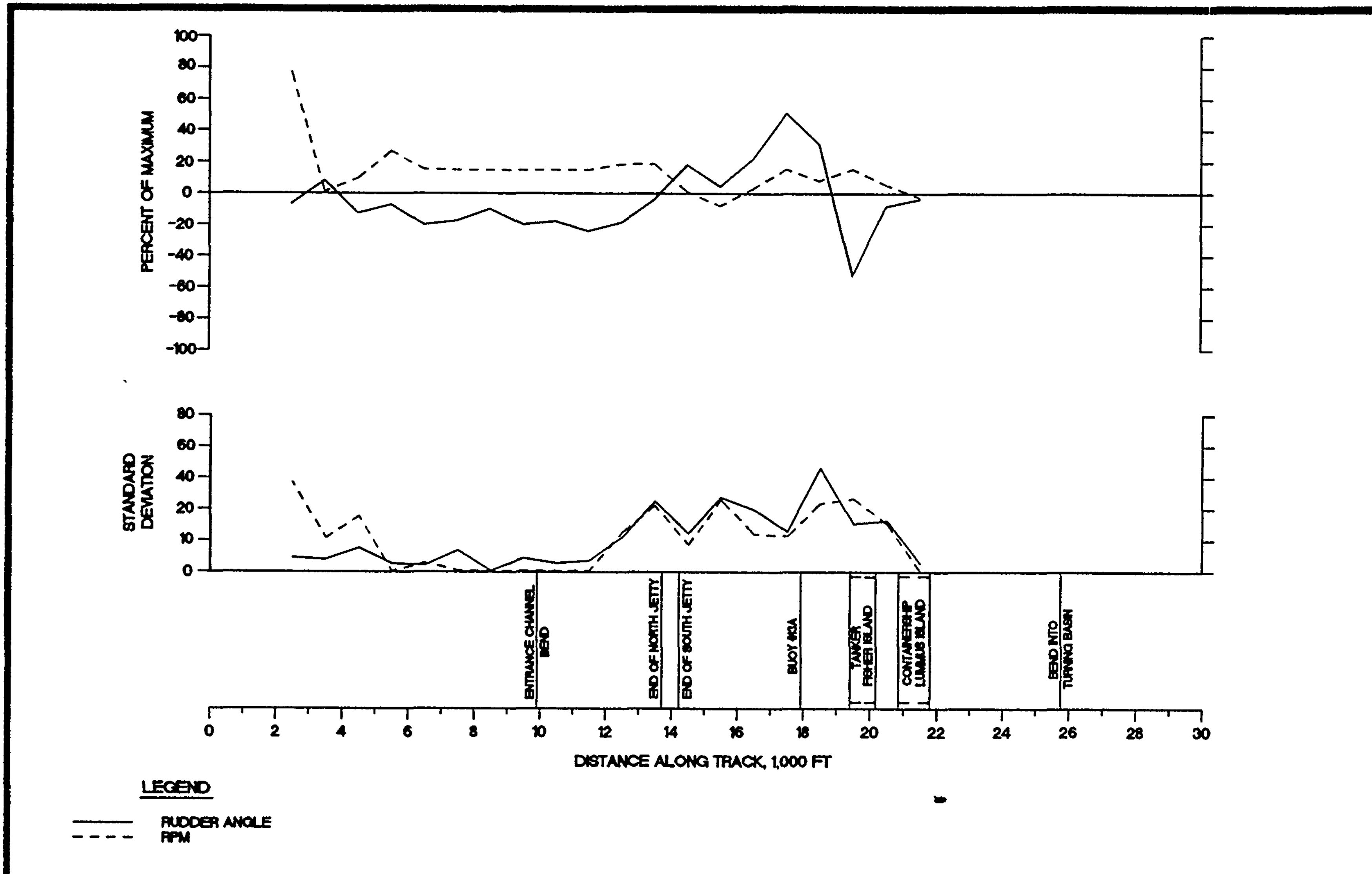


Figure 18. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot D

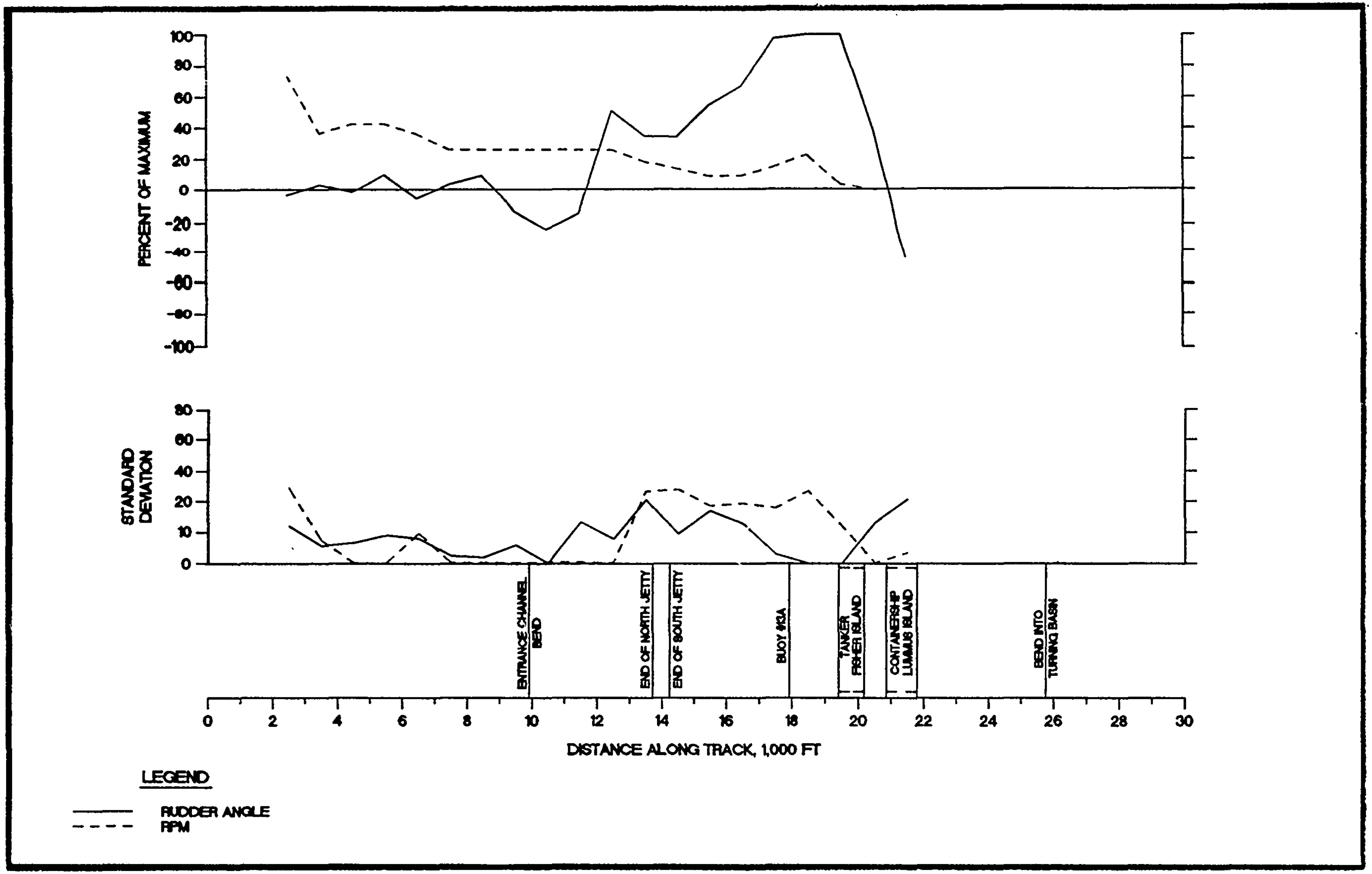


Figure 19. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot C

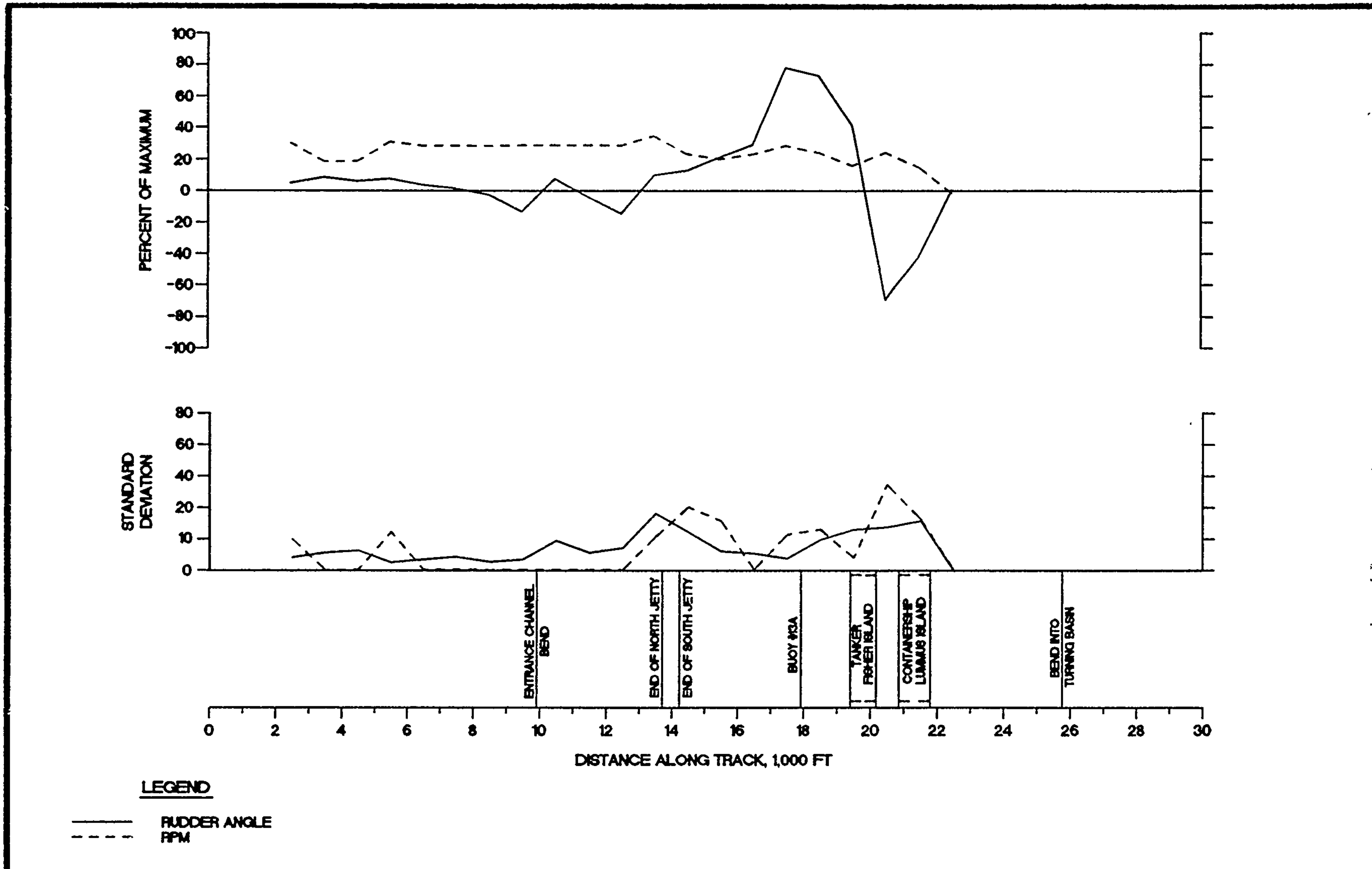


Figure 20. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot D

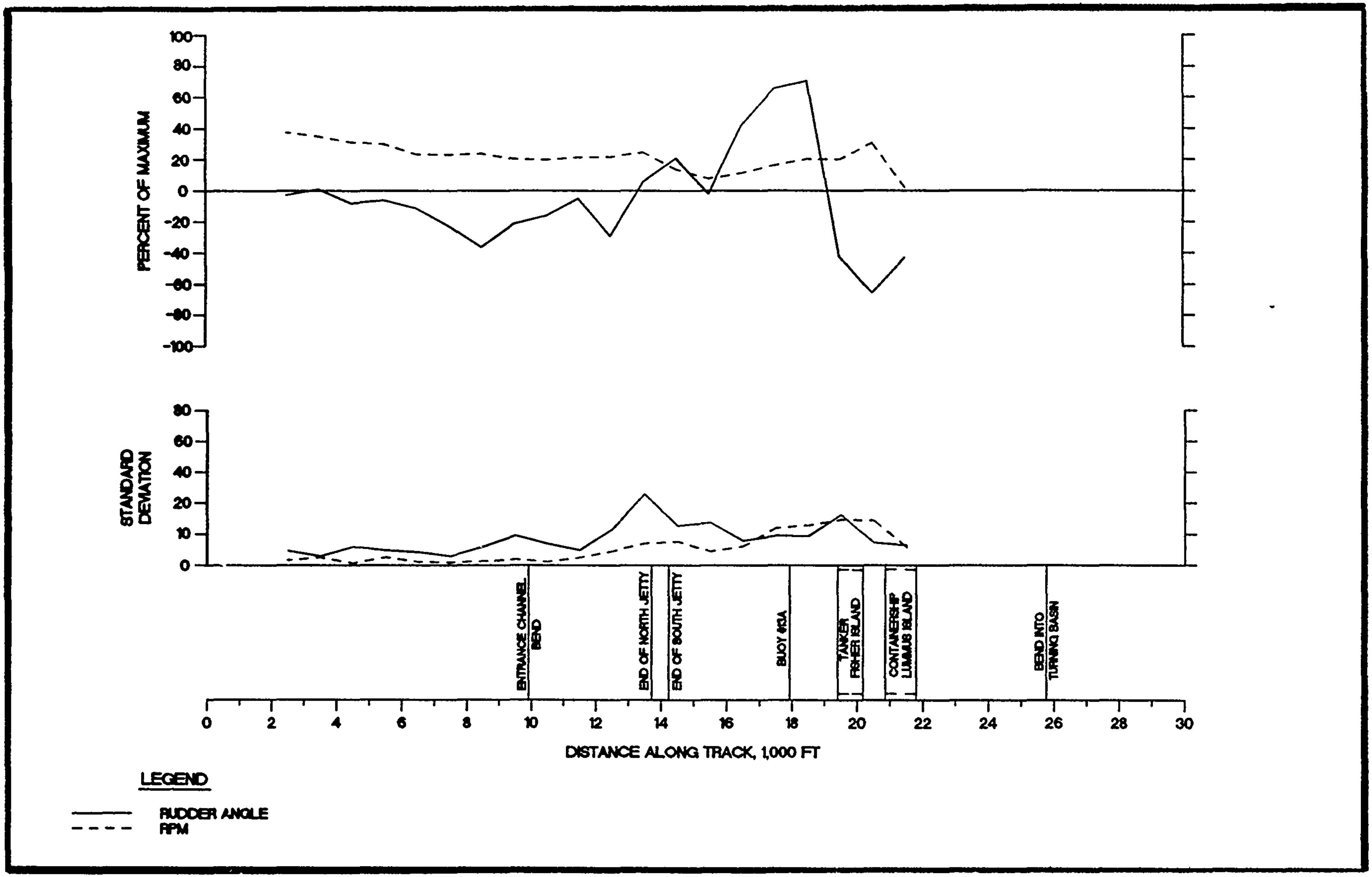


Figure 21. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, inbound, all runs

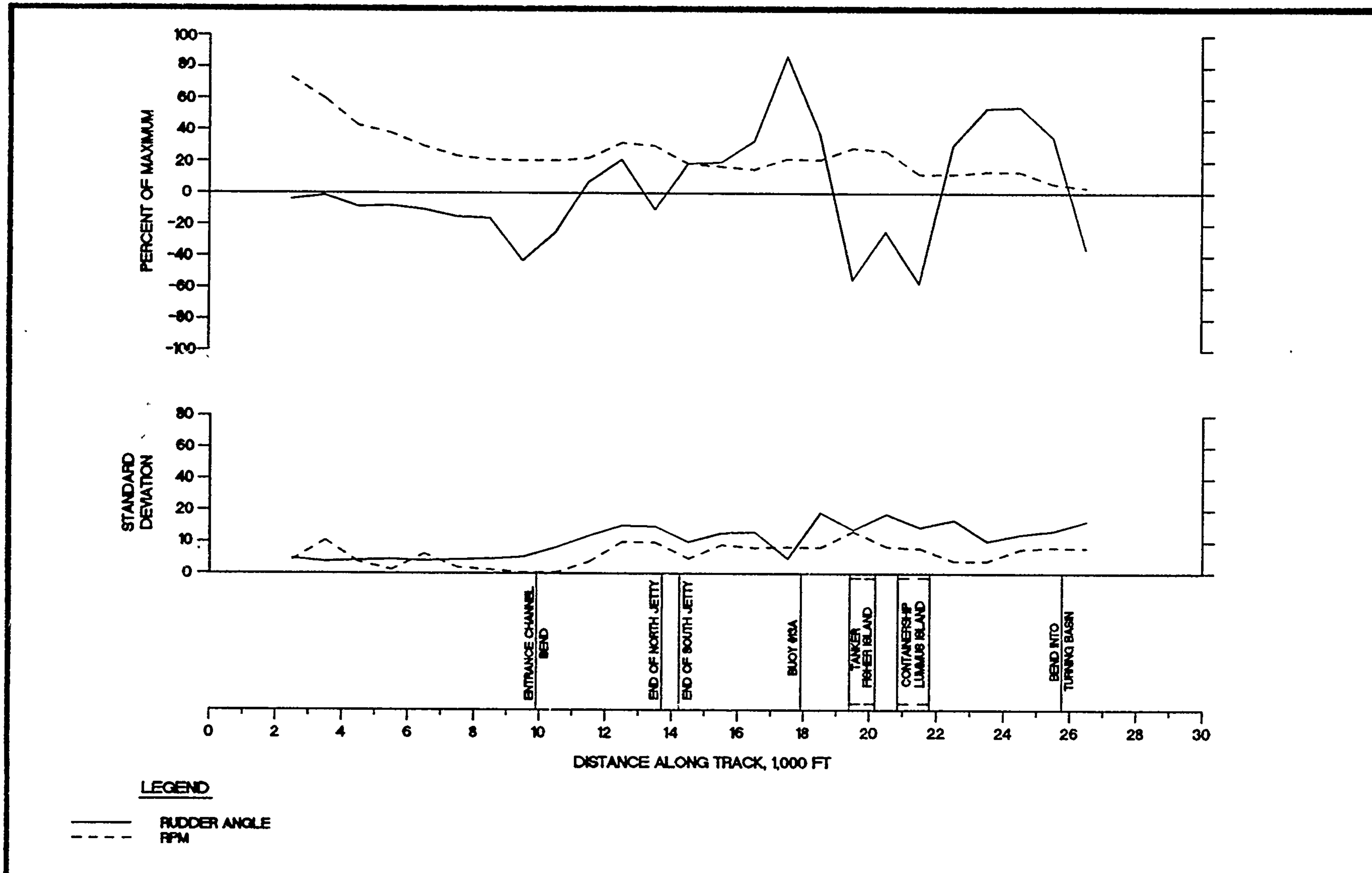


Figure 22. Rudder angle and rpm, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, inbound with tugs, all runs

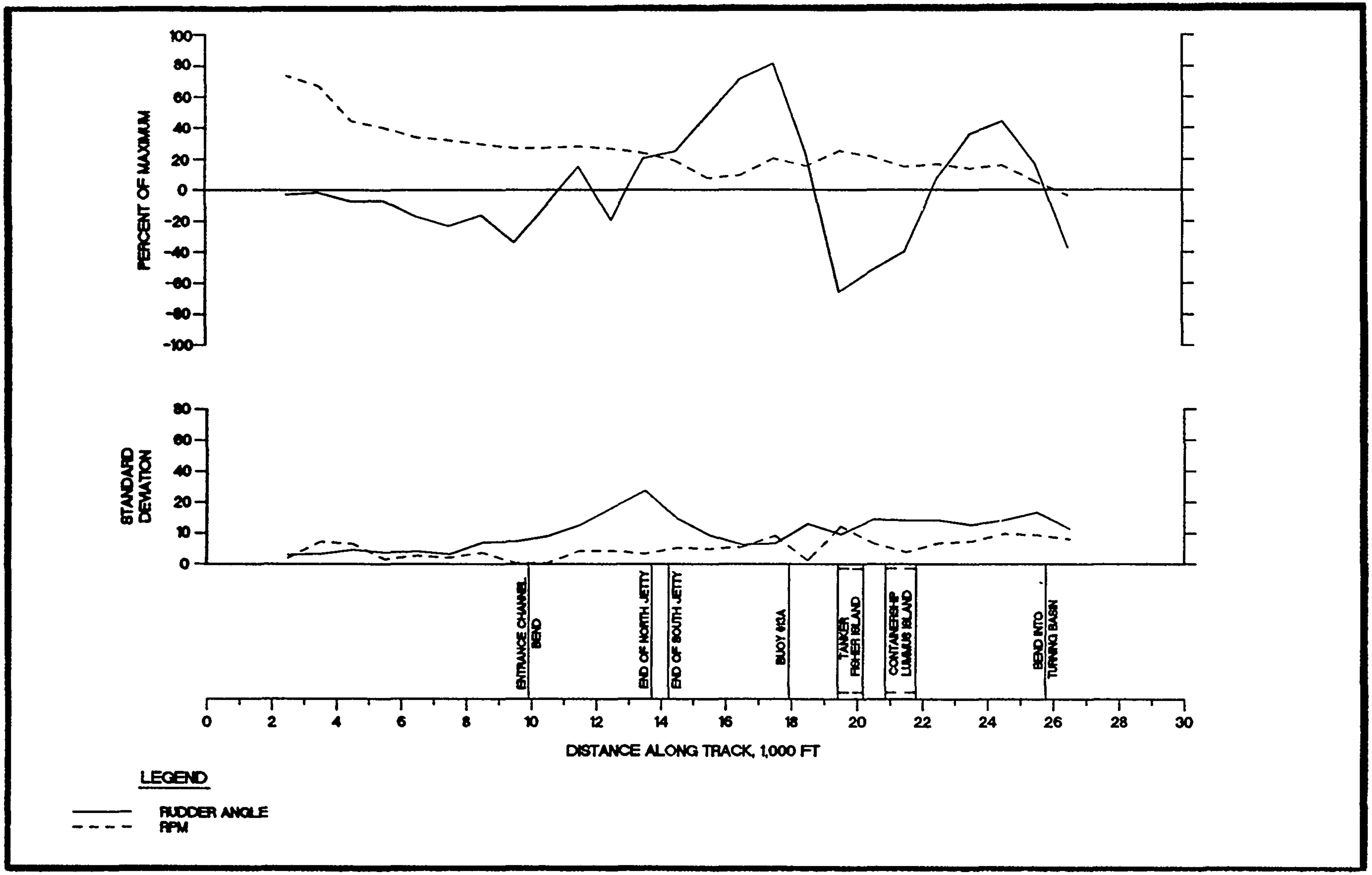


Figure 23. Rudder angle and rpm, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, inbound with tugs, all runs

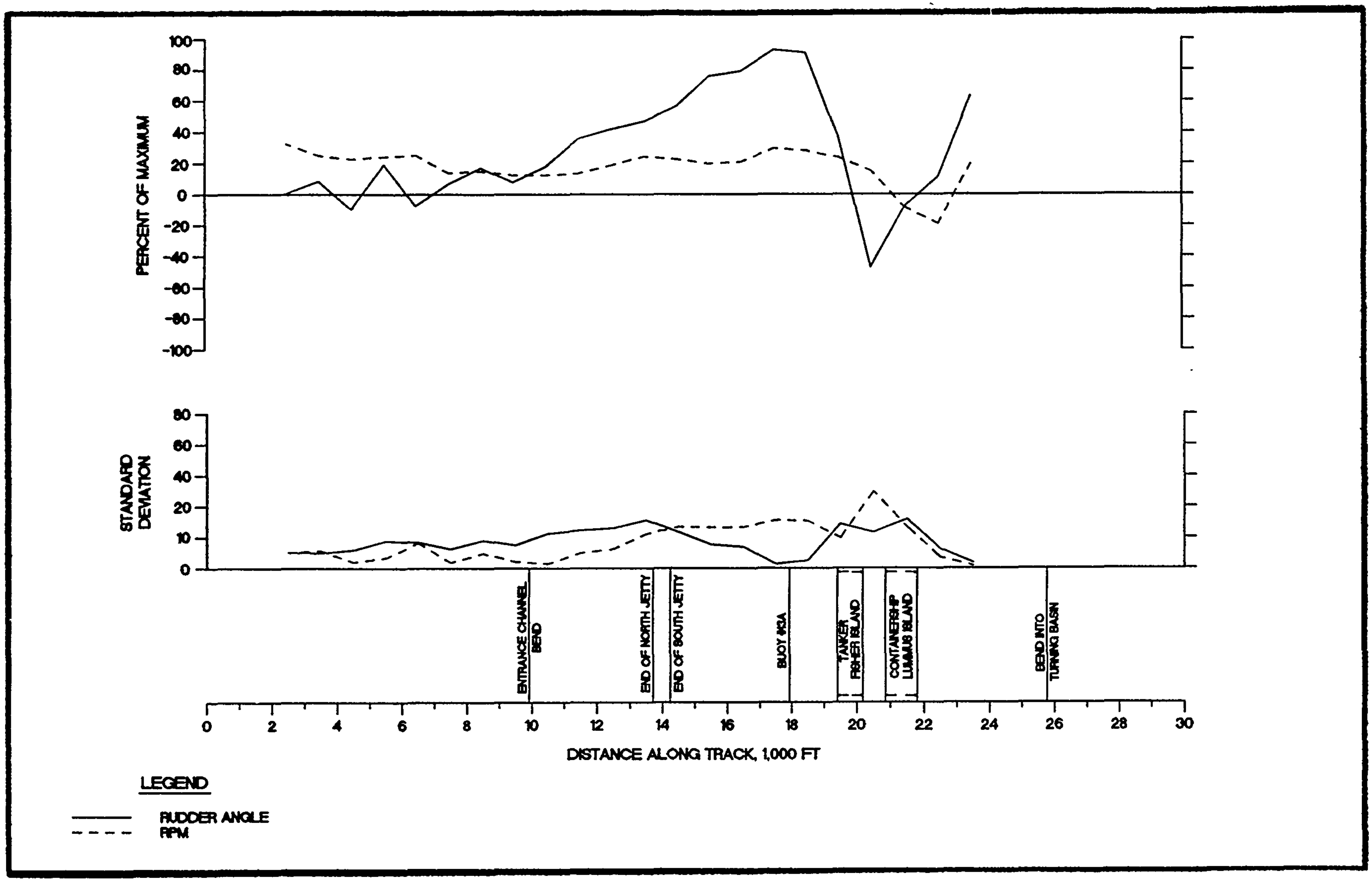


Figure 24. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, inbound, all runs

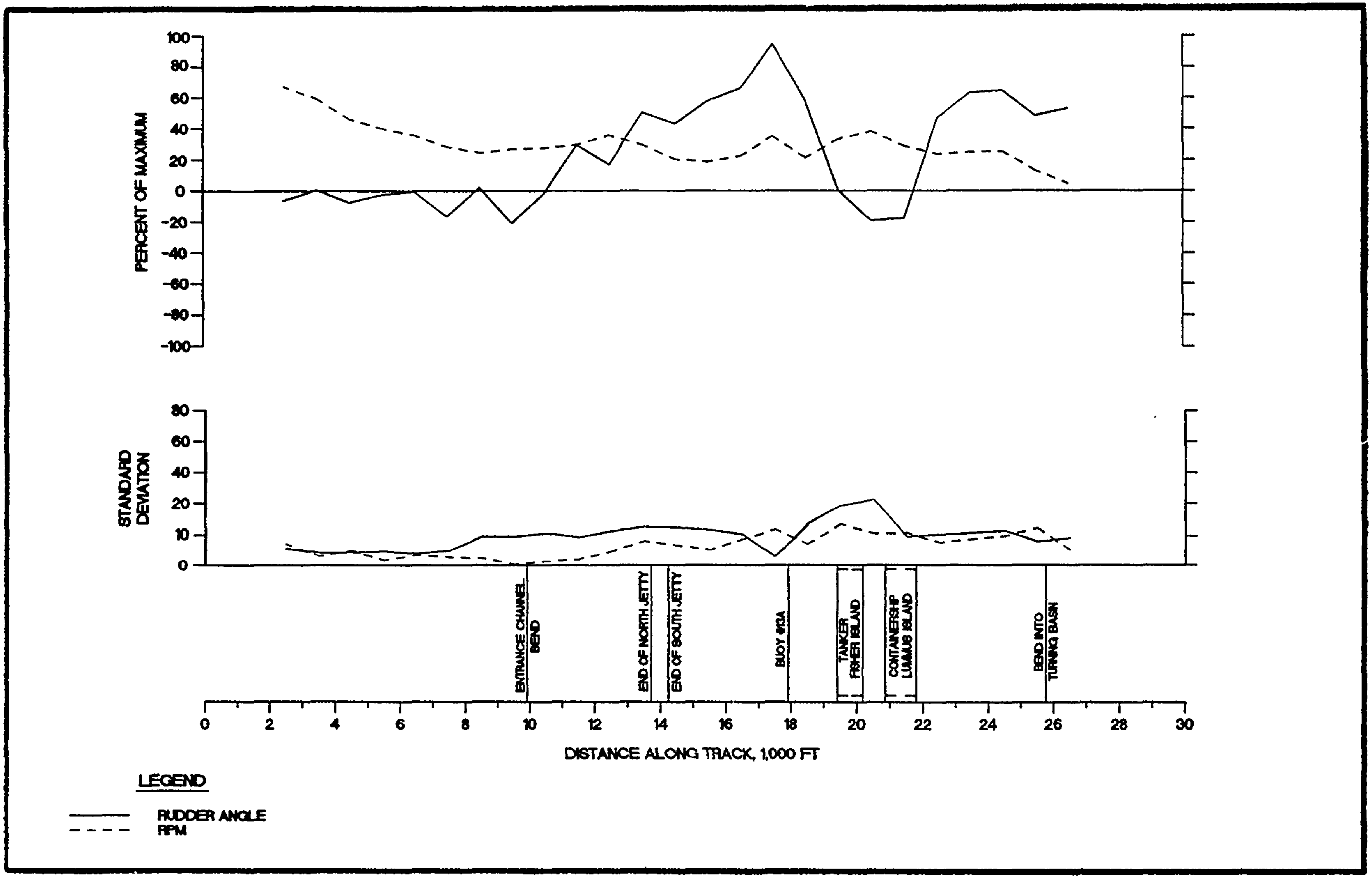


Figure 25. Rudder angle and rpm, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

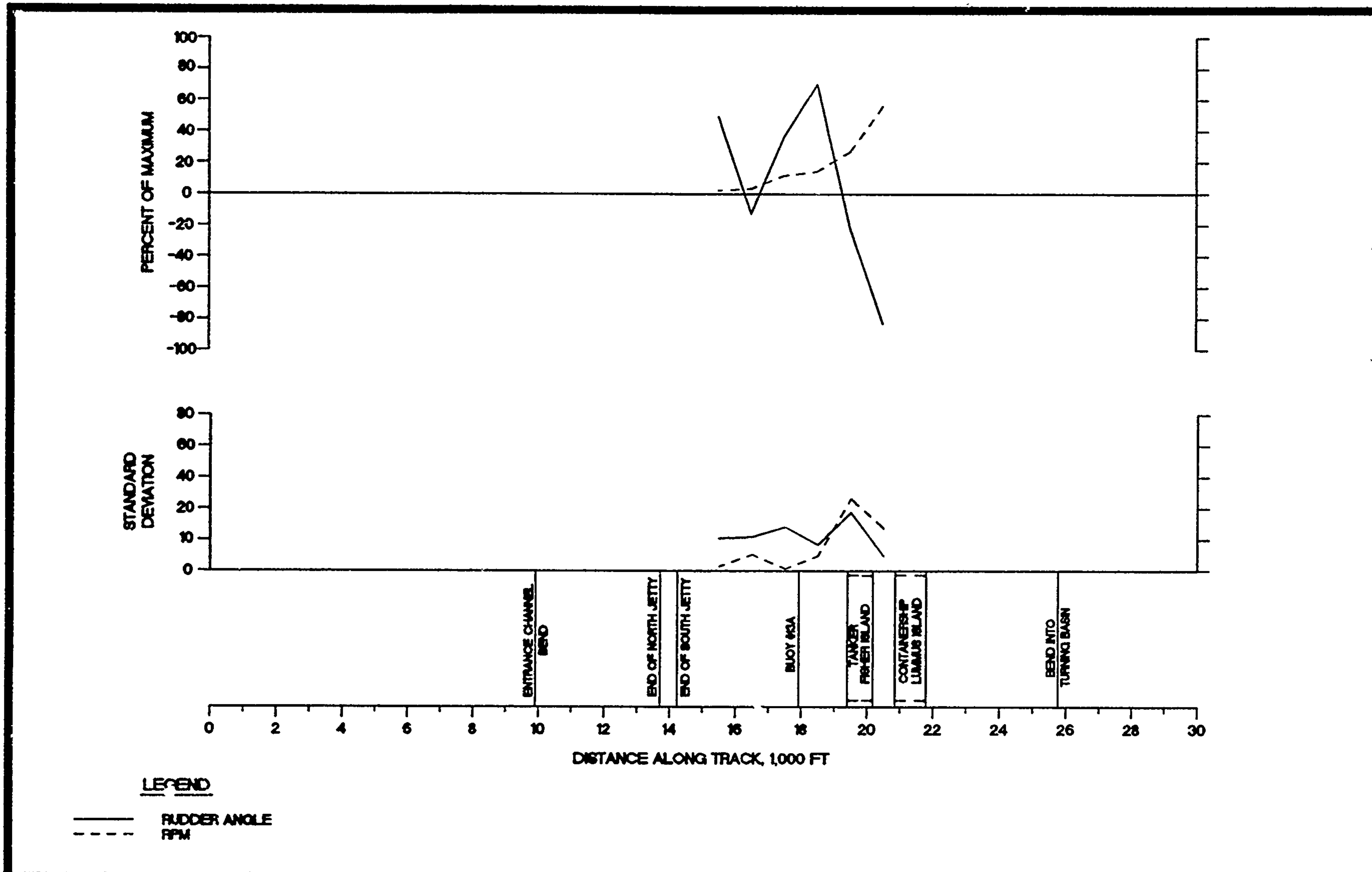


Figure 26. Rudder angle and rpm, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot southeast wind, inbound, all runs

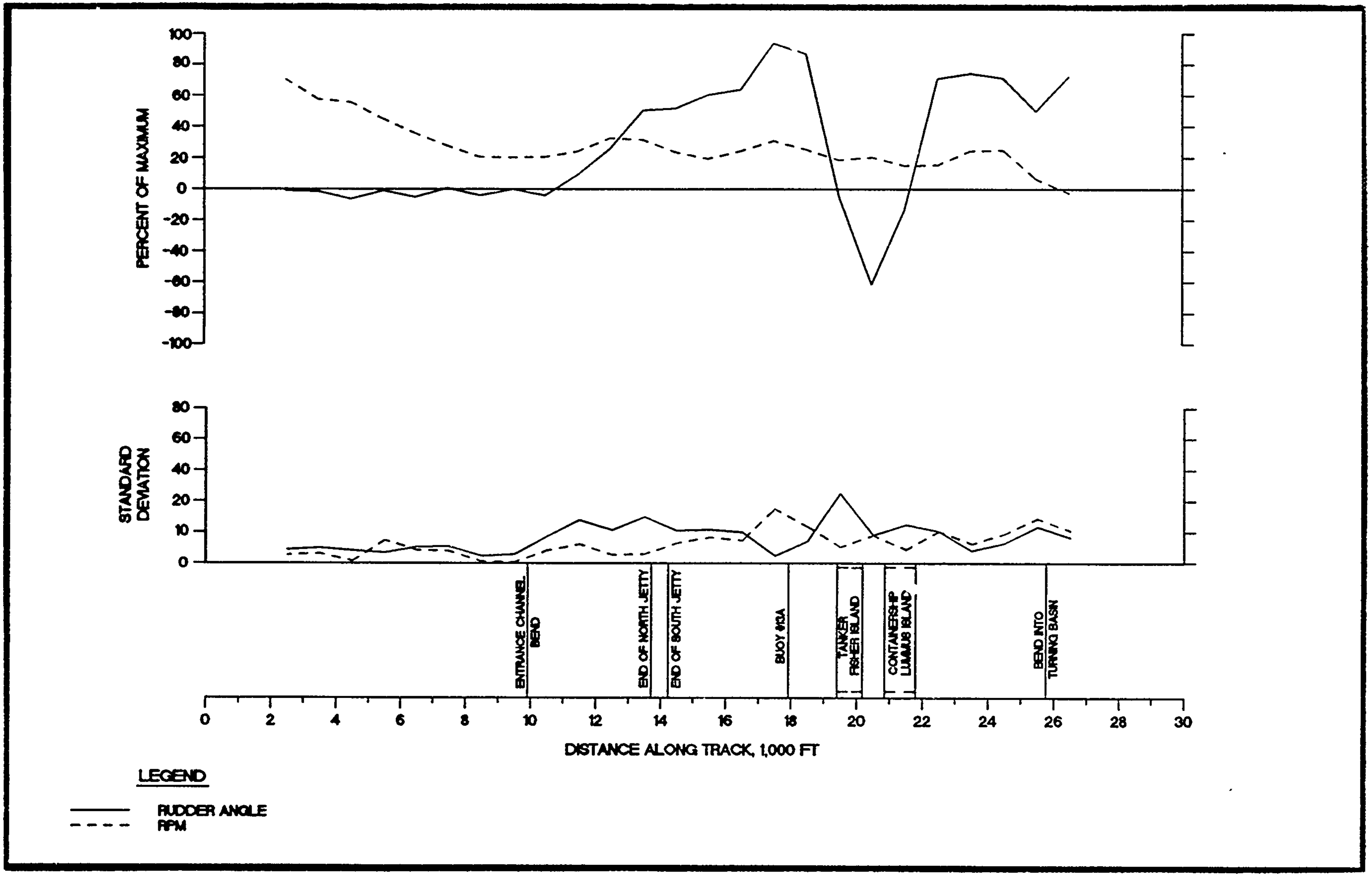


Figure 27. Rudder angle and rpm, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

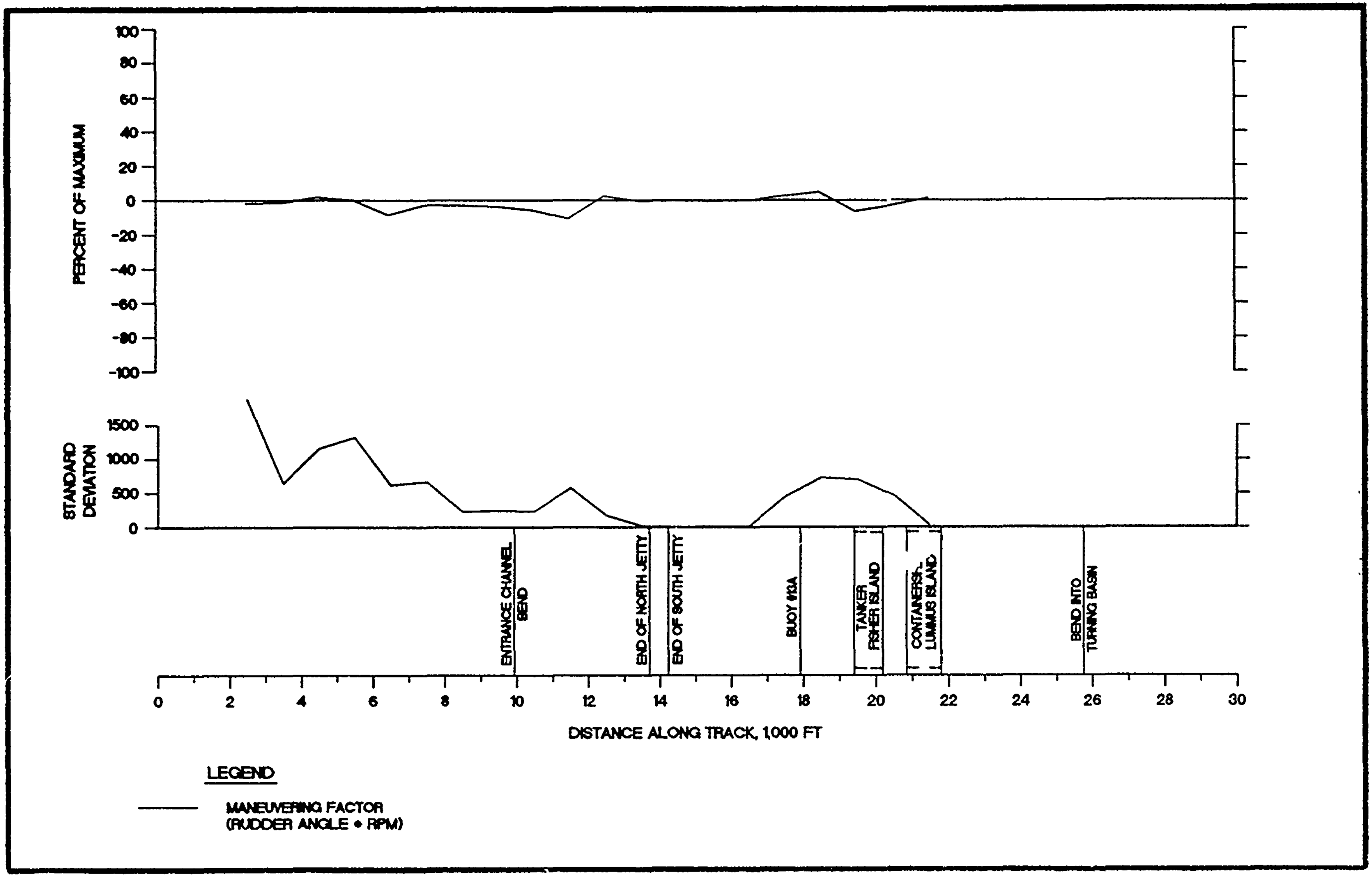


Figure 28. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot C

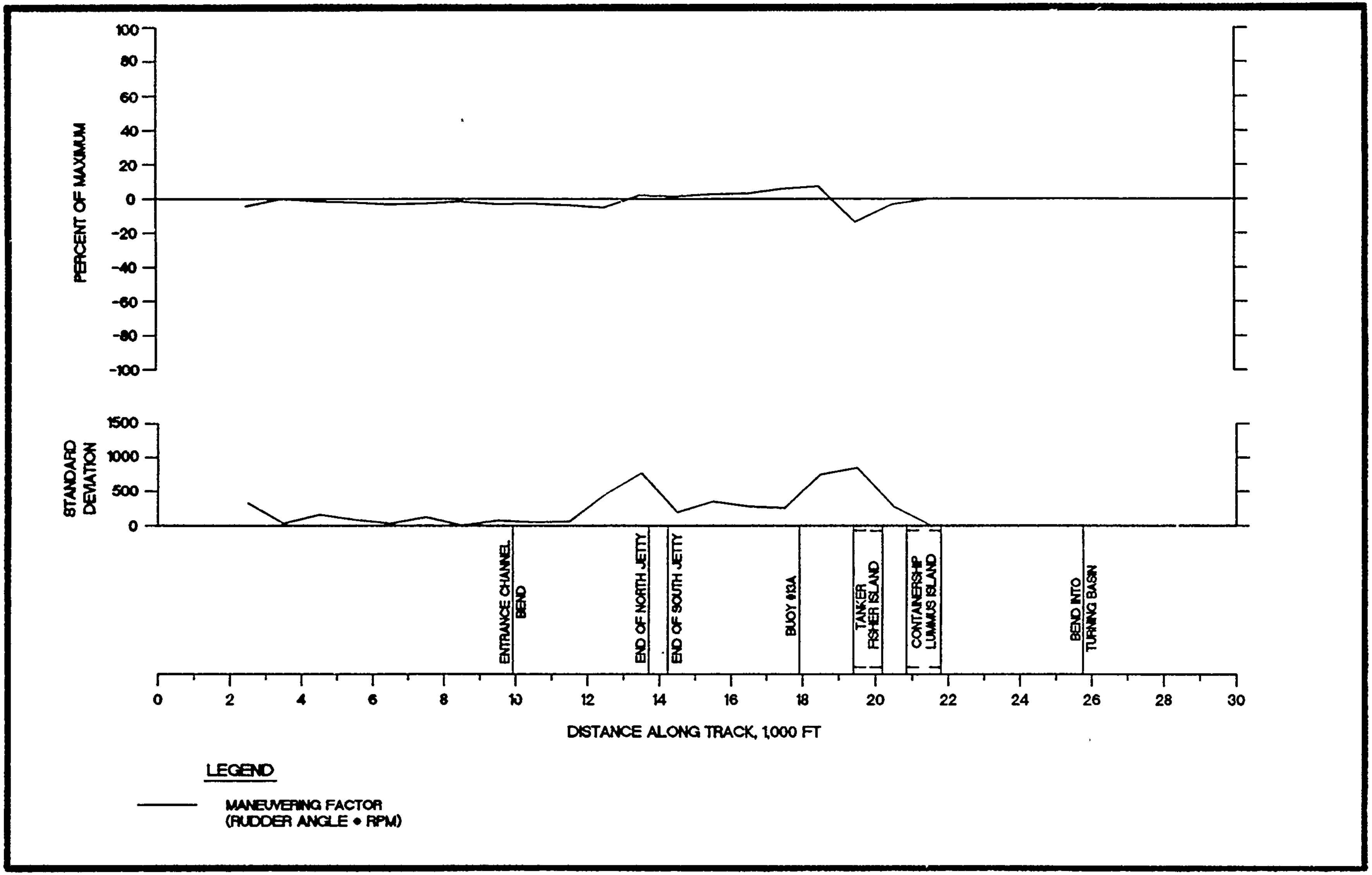


Figure 29. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot D

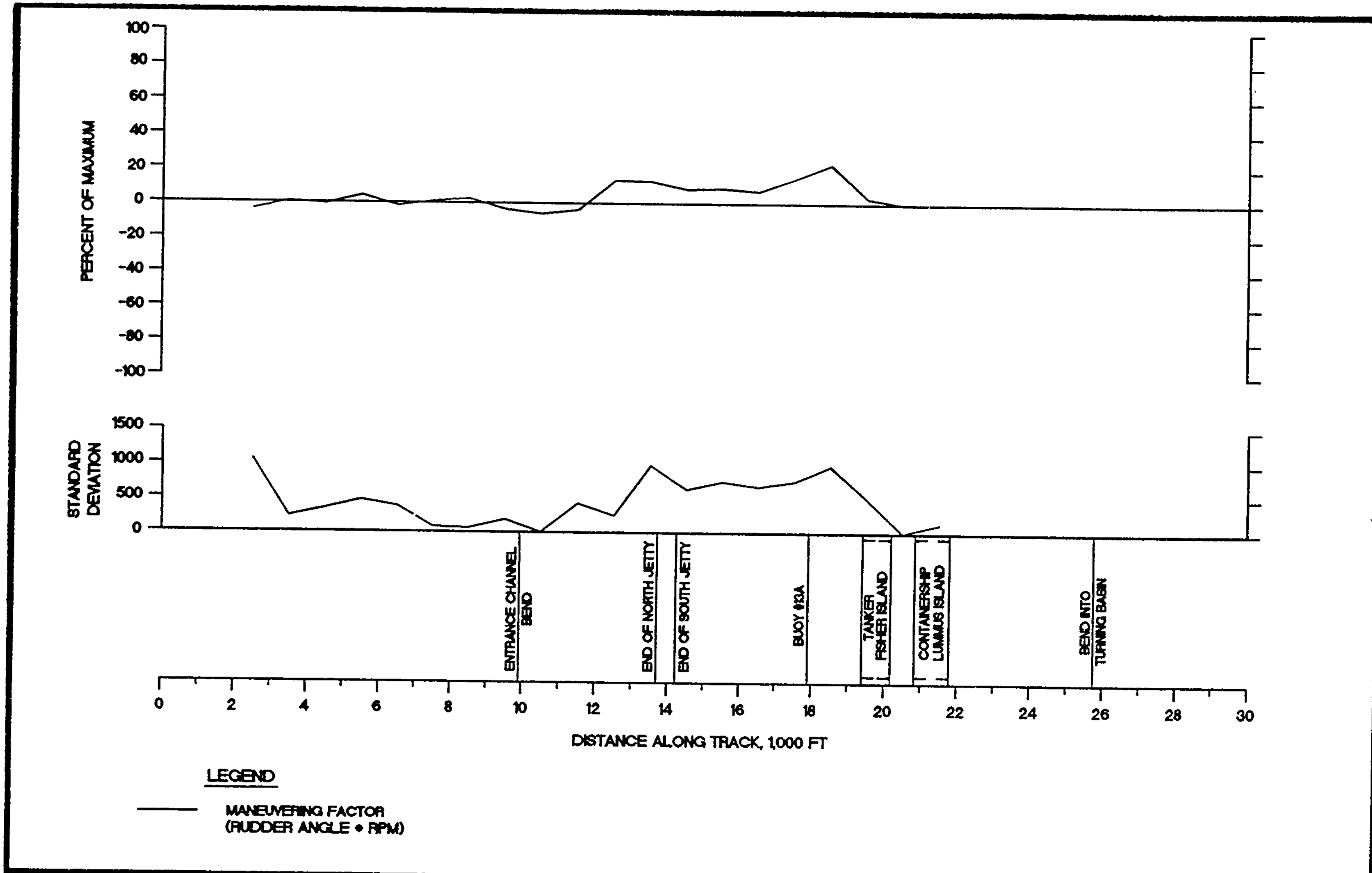


Figure 30. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot C

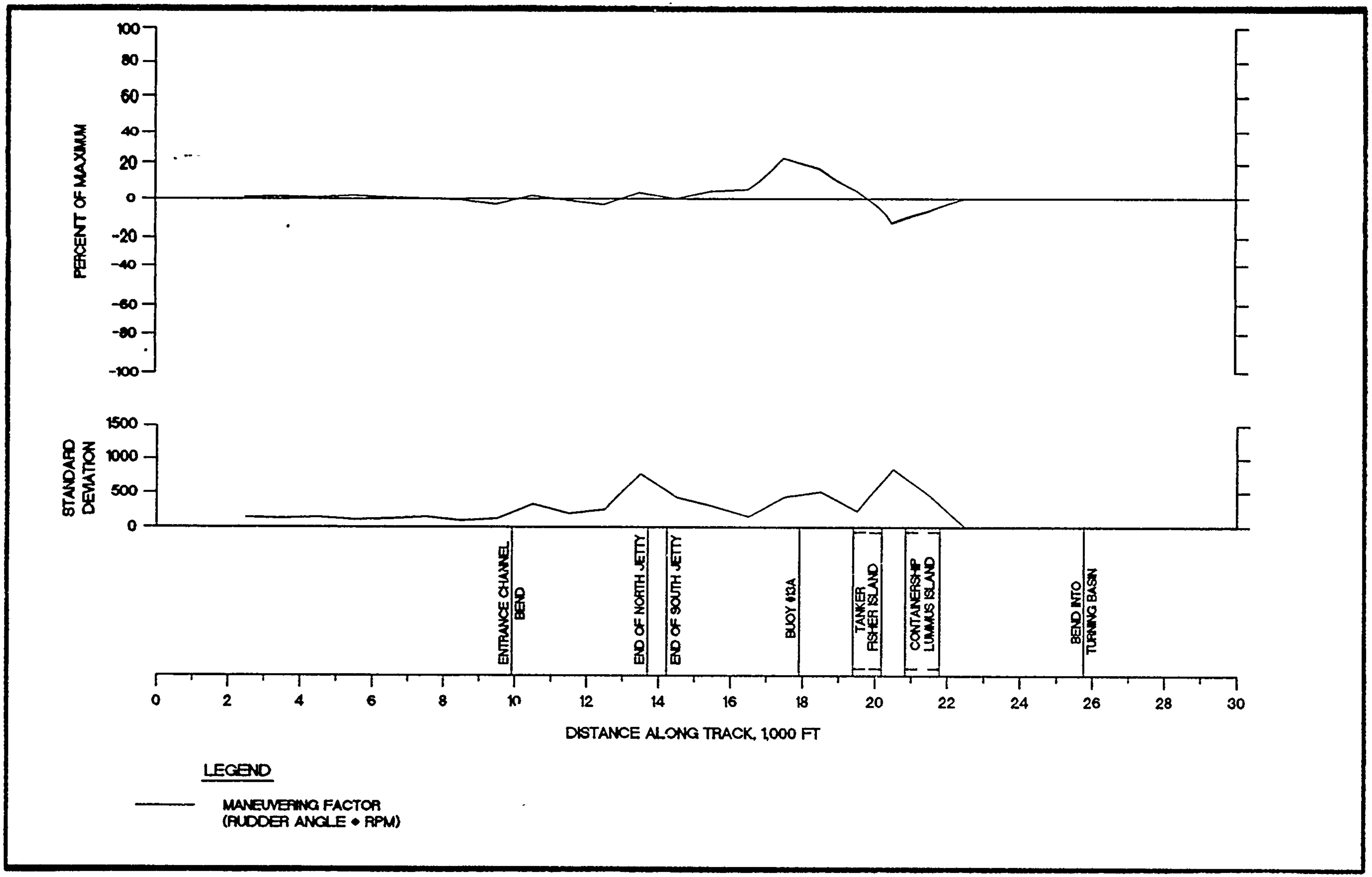


Figure 31. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot D

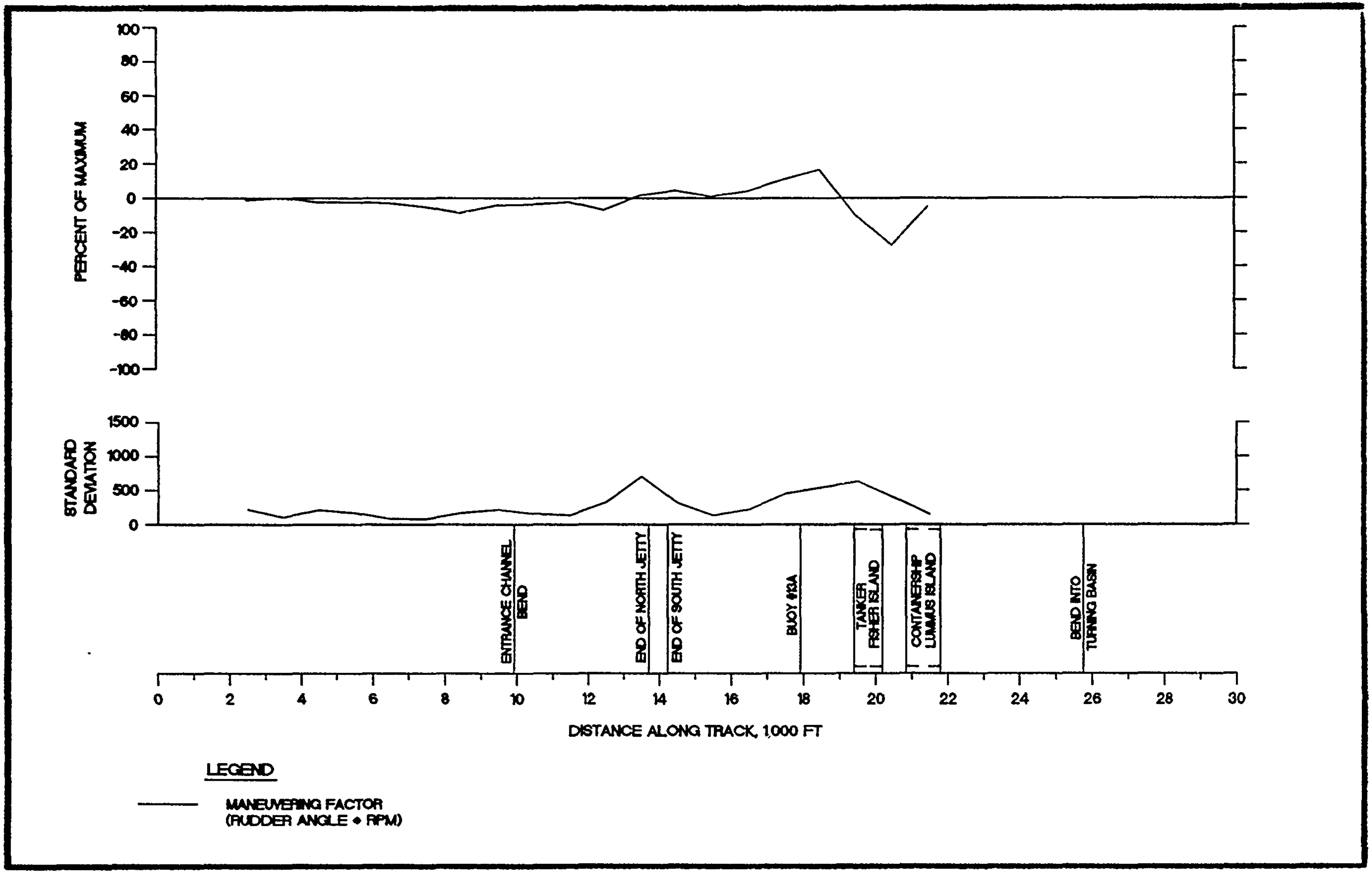


Figure 32. Maneuvering factor, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, inbound, all runs

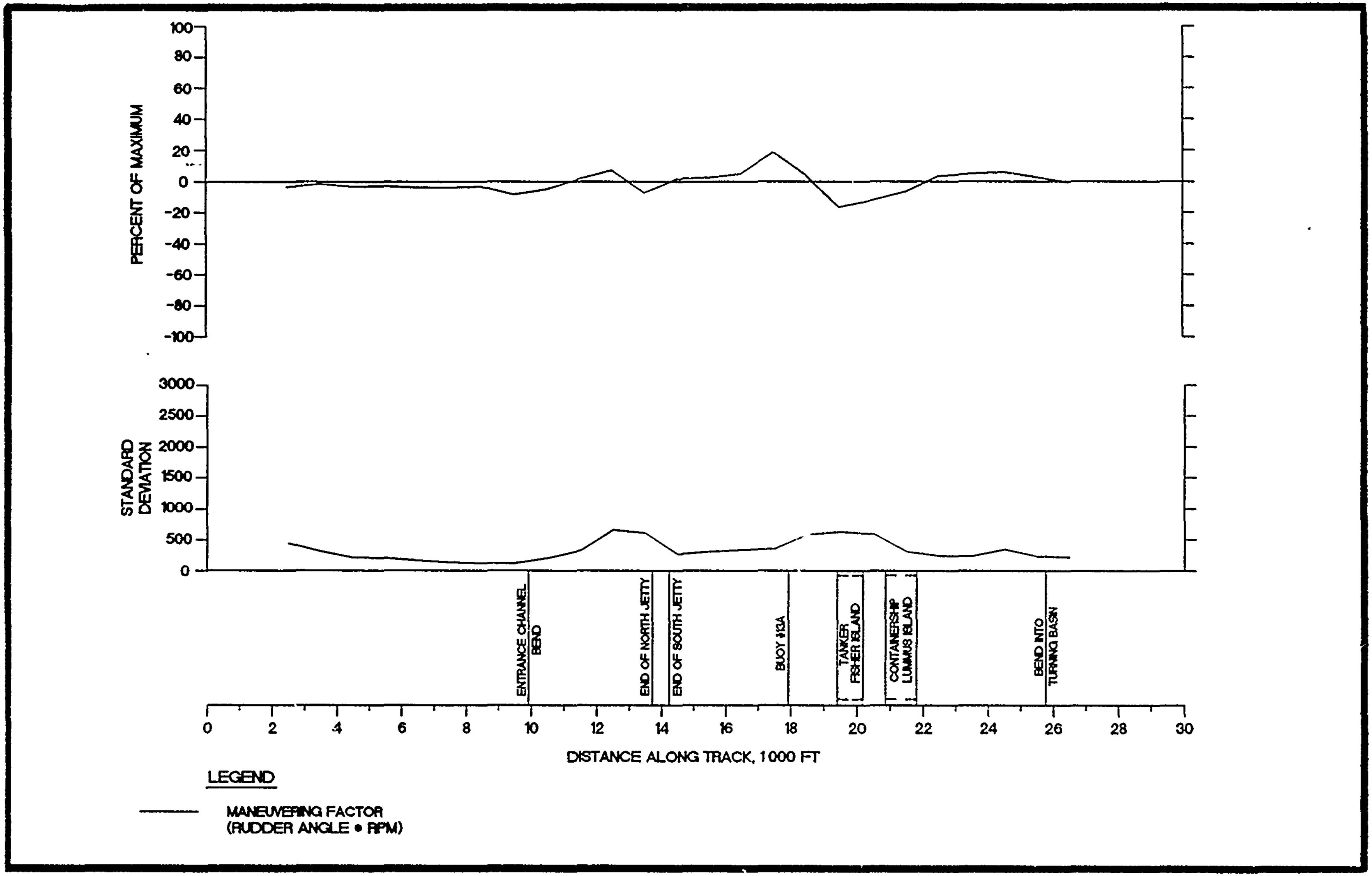


Figure 33. Maneuvering factor, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, inbound with tugs, all runs

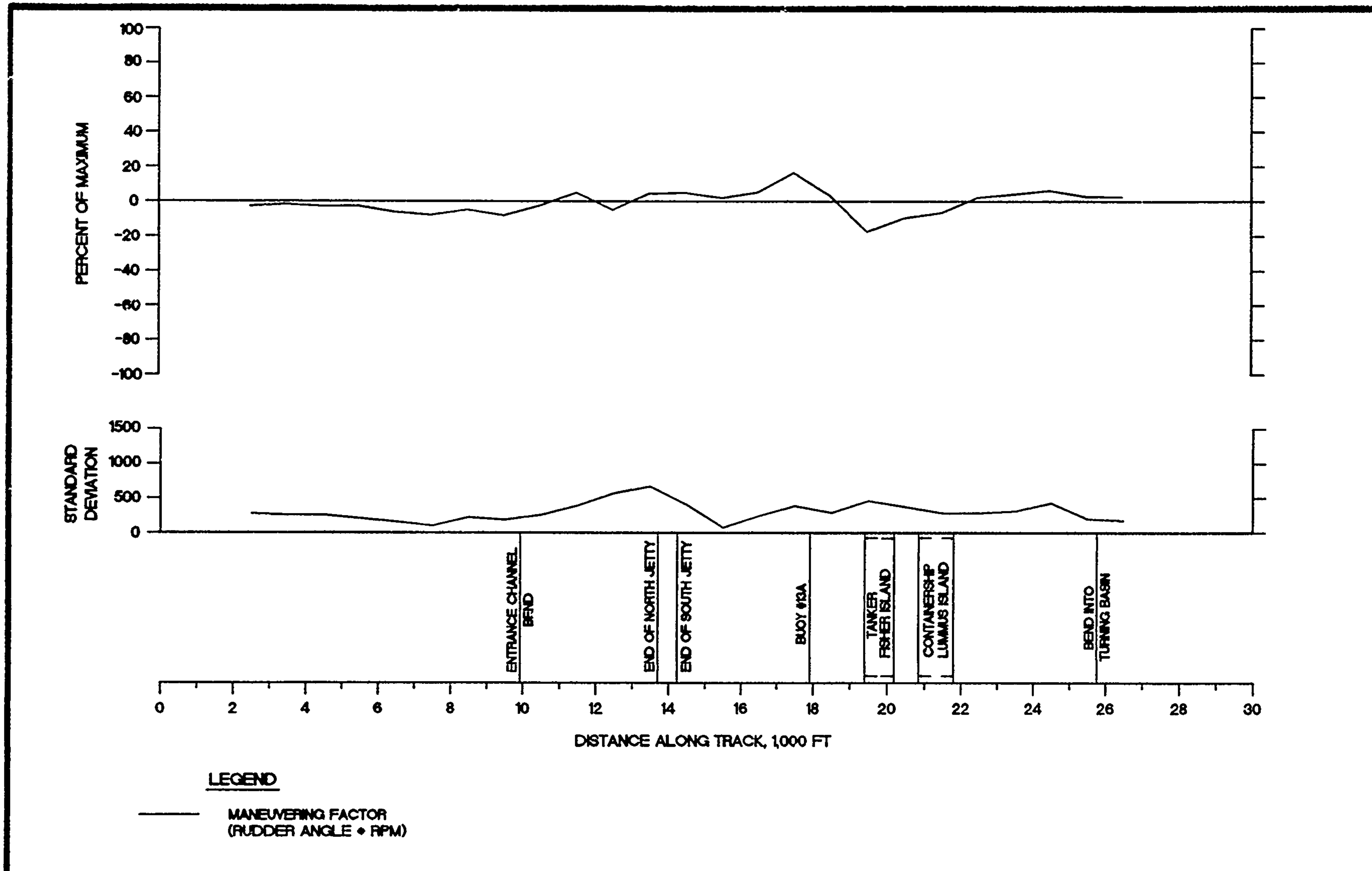


Figure 34. Maneuvering factor, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, inbound with tugs, all runs

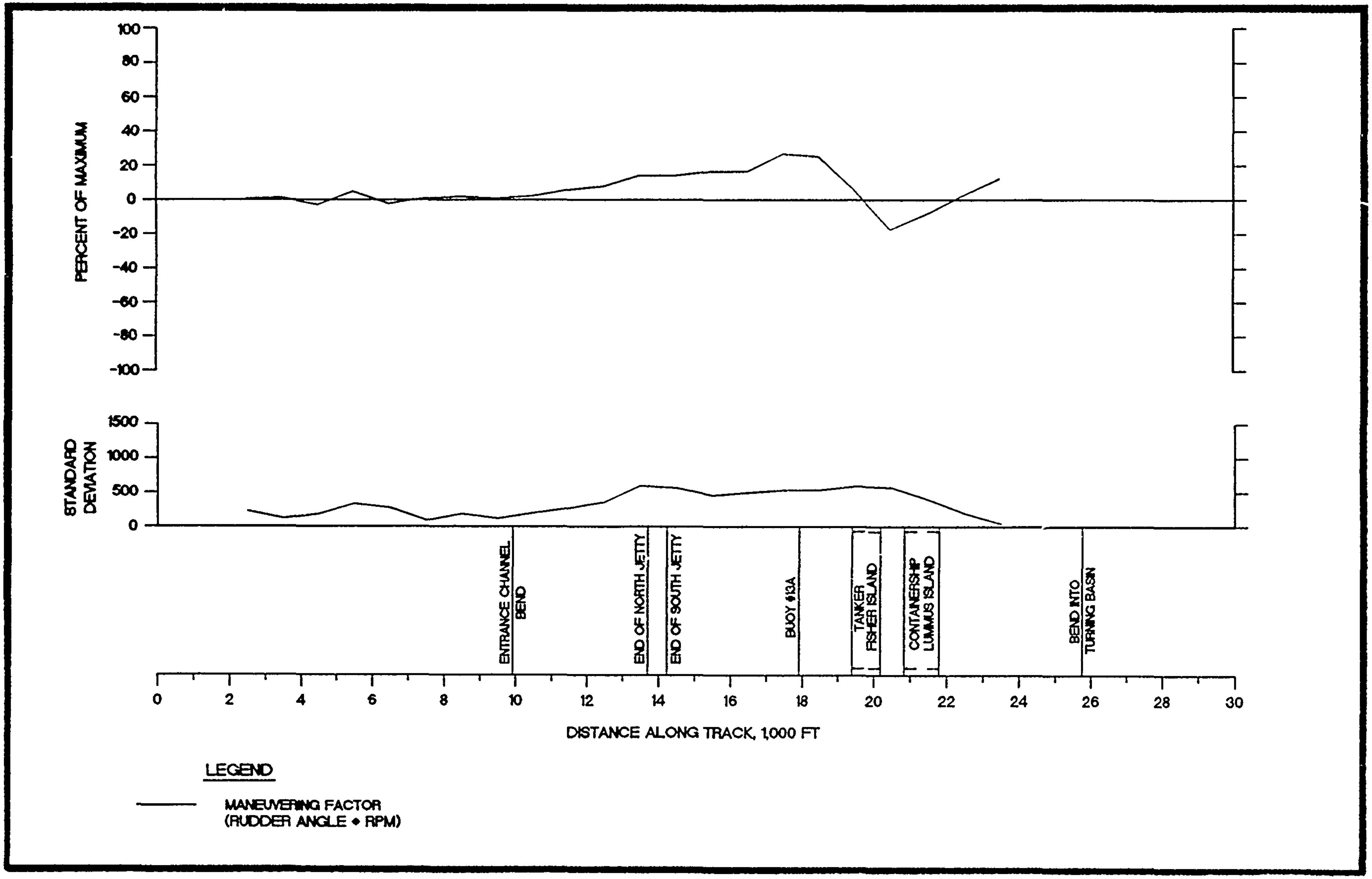


Figure 35. Maneuvering factor, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, inbound, all runs

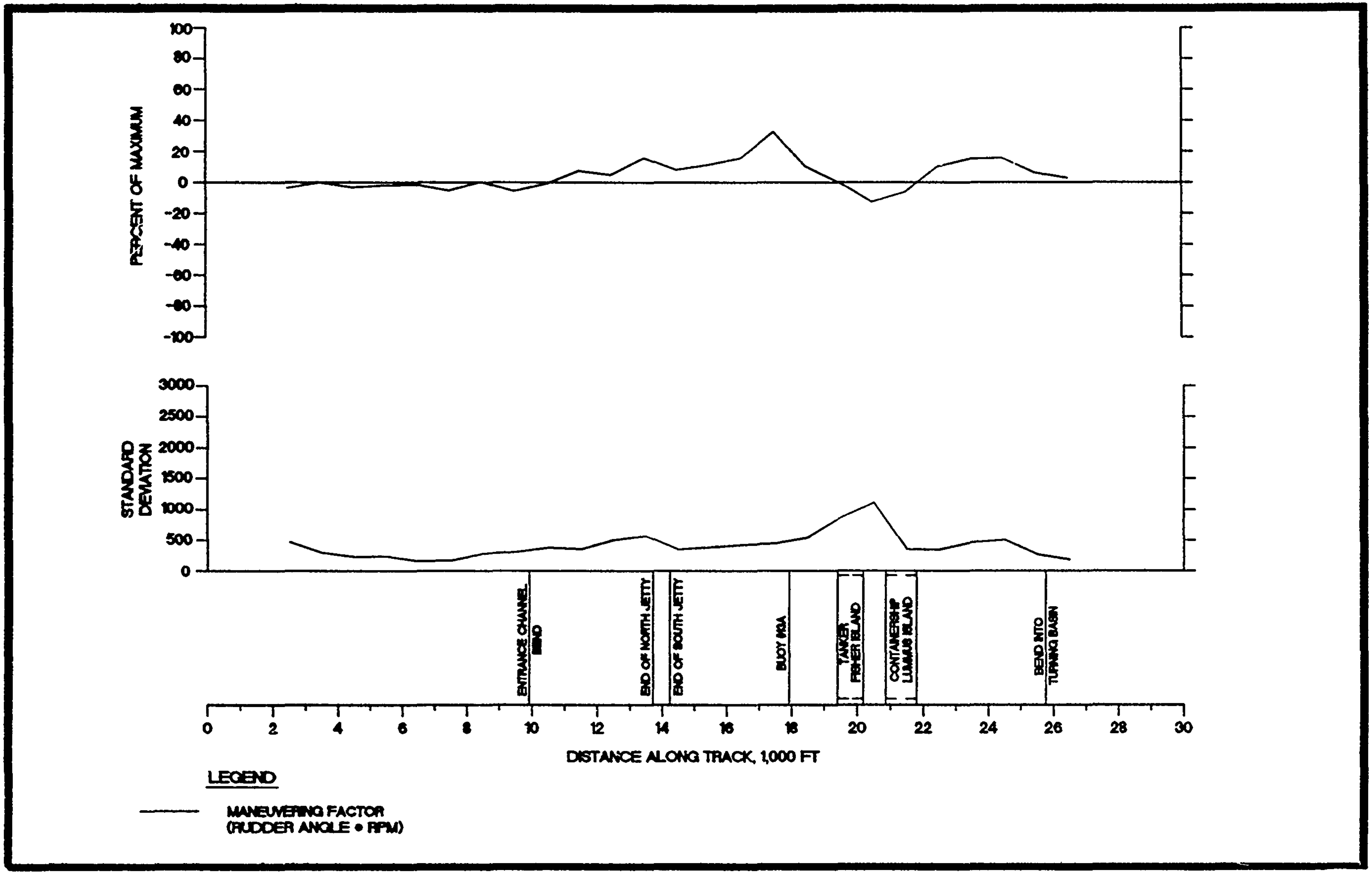


Figure 36. Maneuvering factor, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

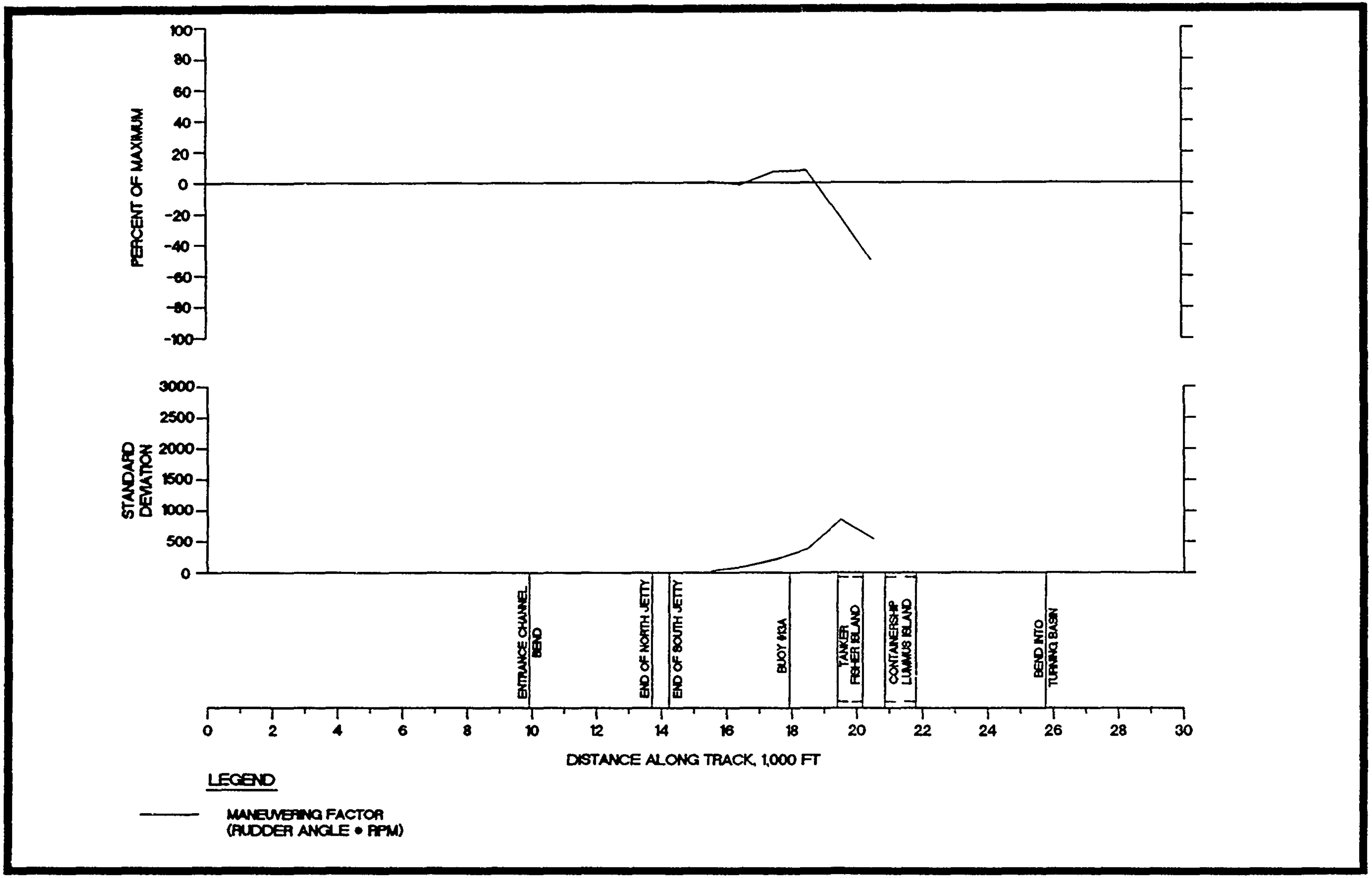


Figure 37. Maneuvering factor, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot southeast wind, inbound, all runs

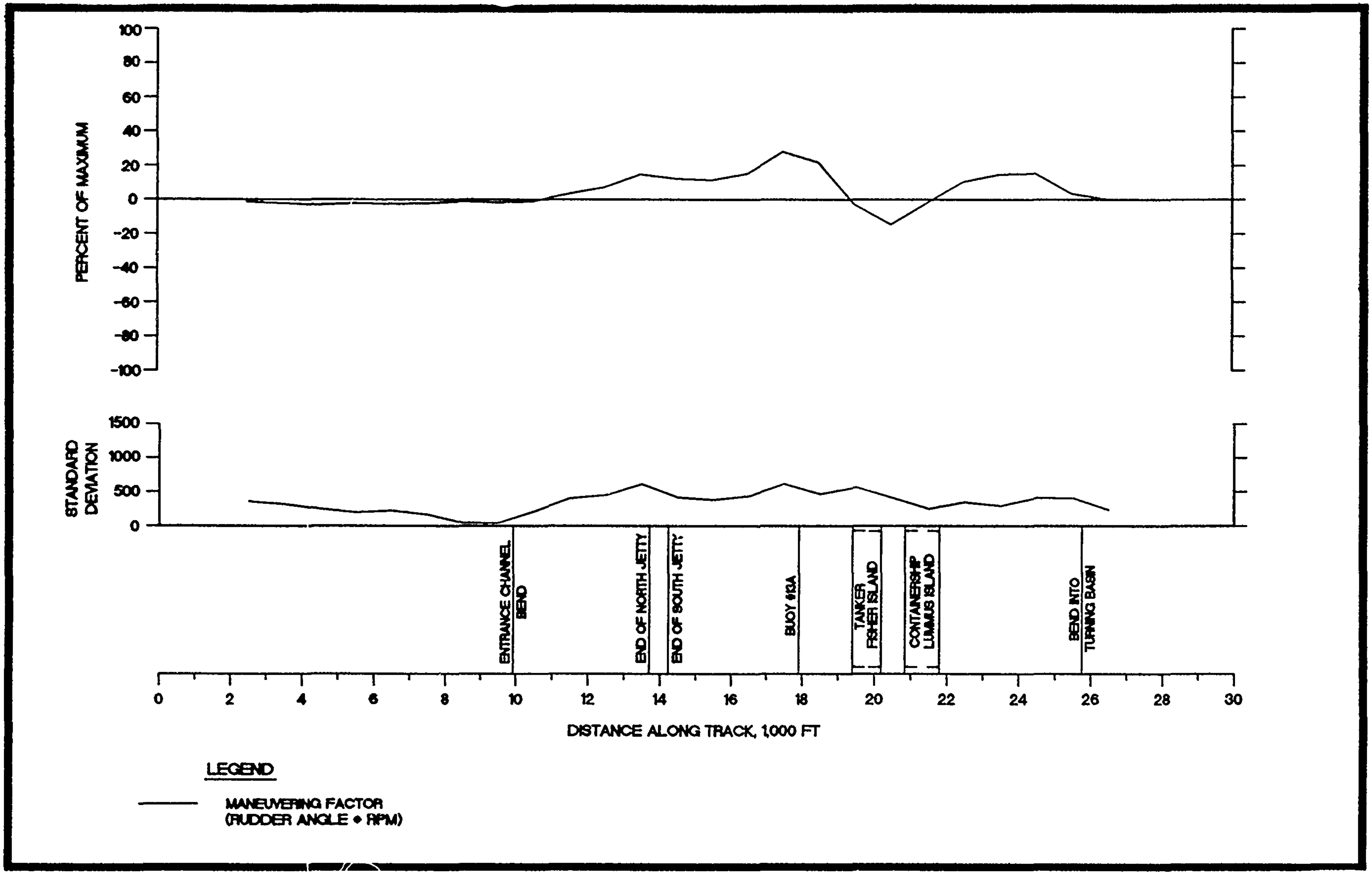


Figure 38. Maneuvering factor, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

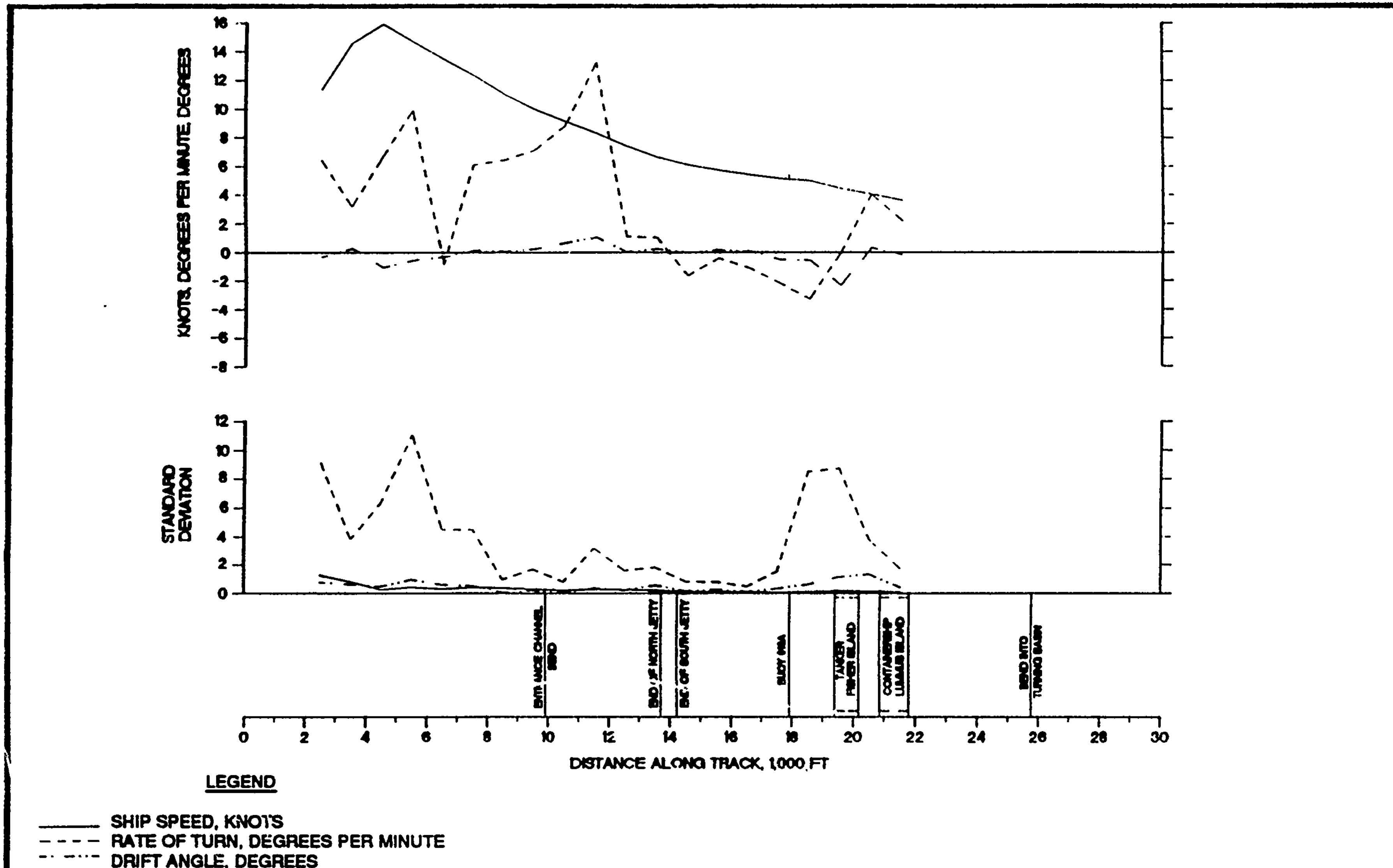


Figure 39. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot C

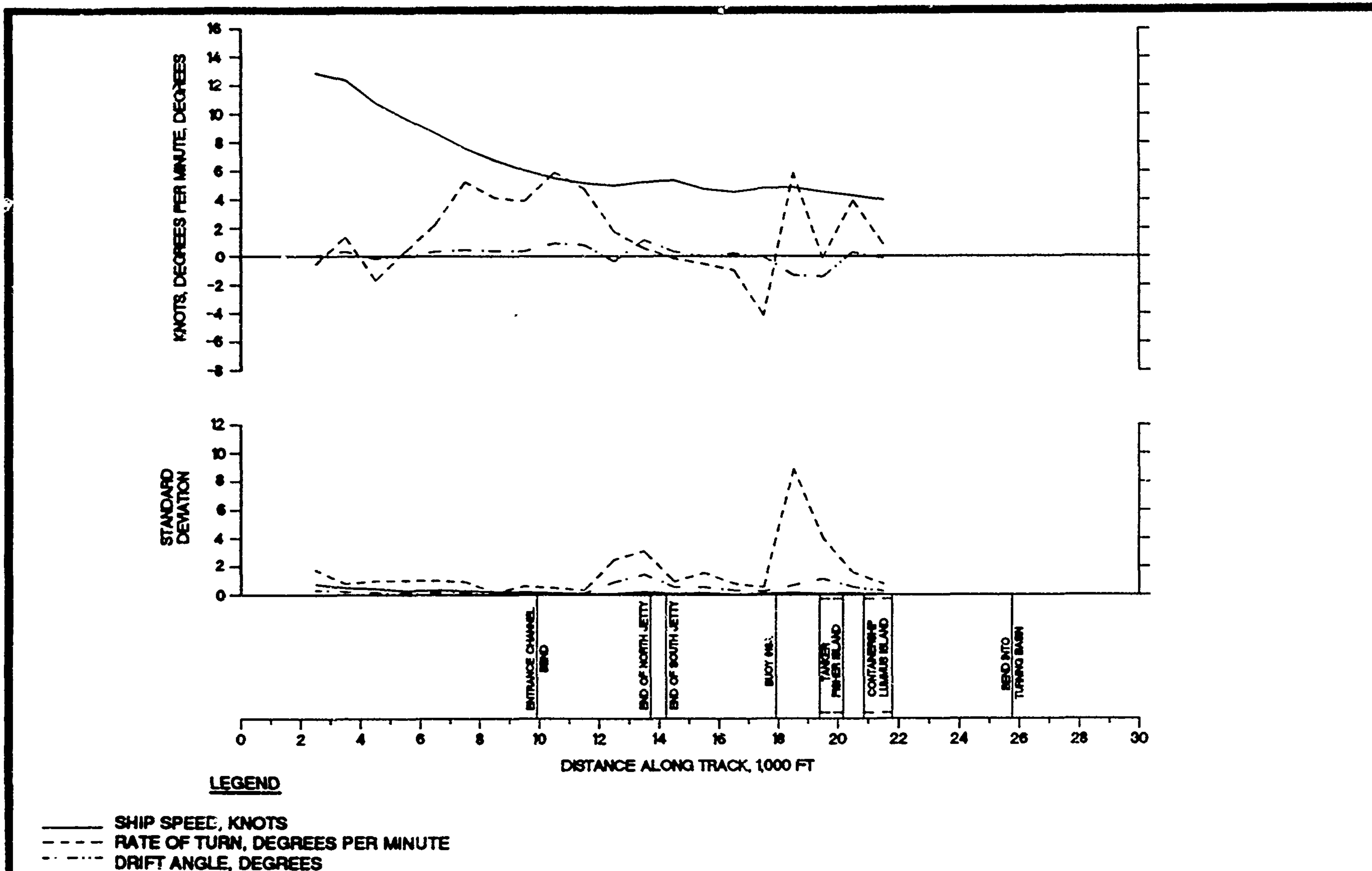


Figure 40. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot D

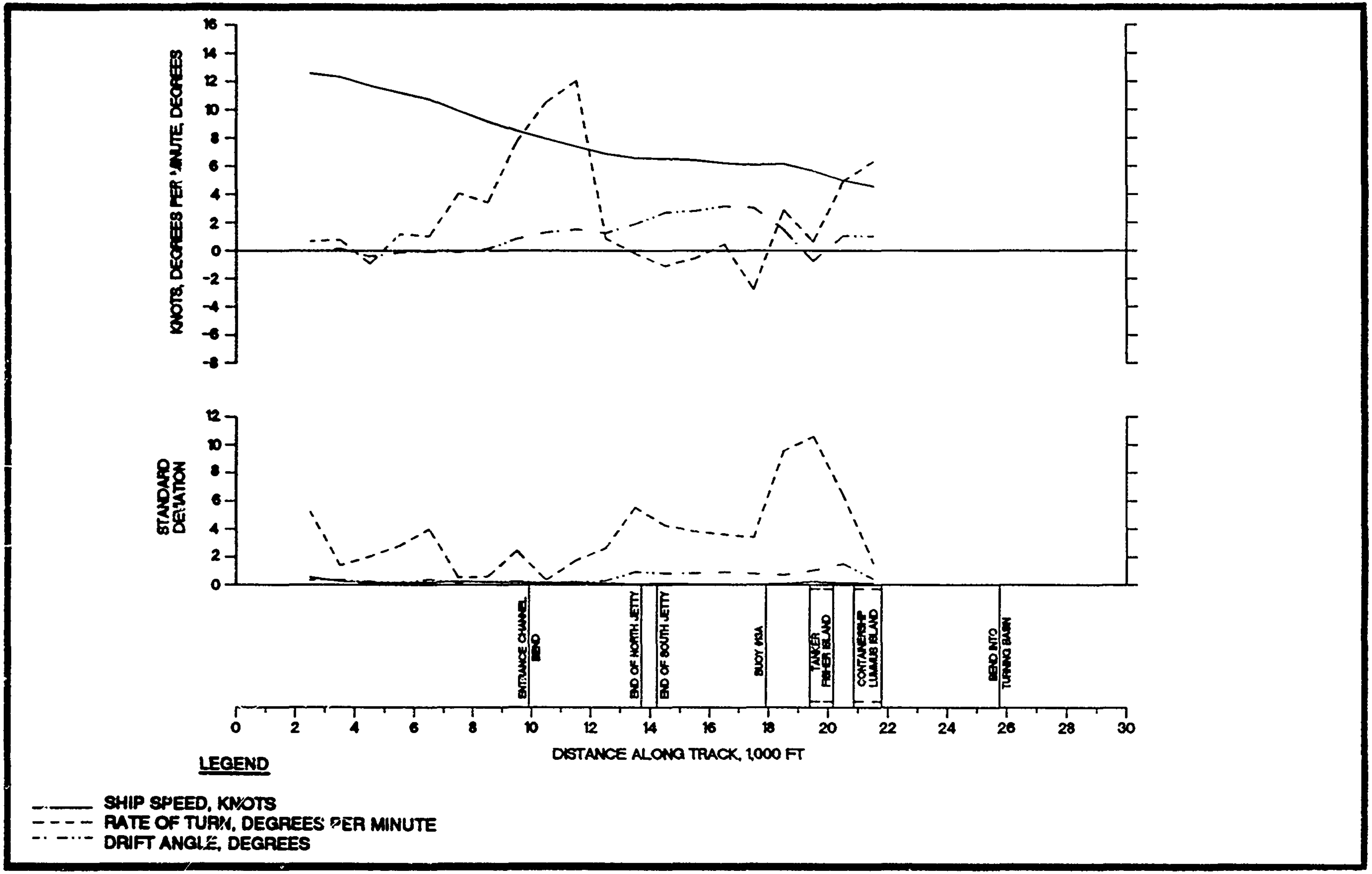


Figure 41. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot C

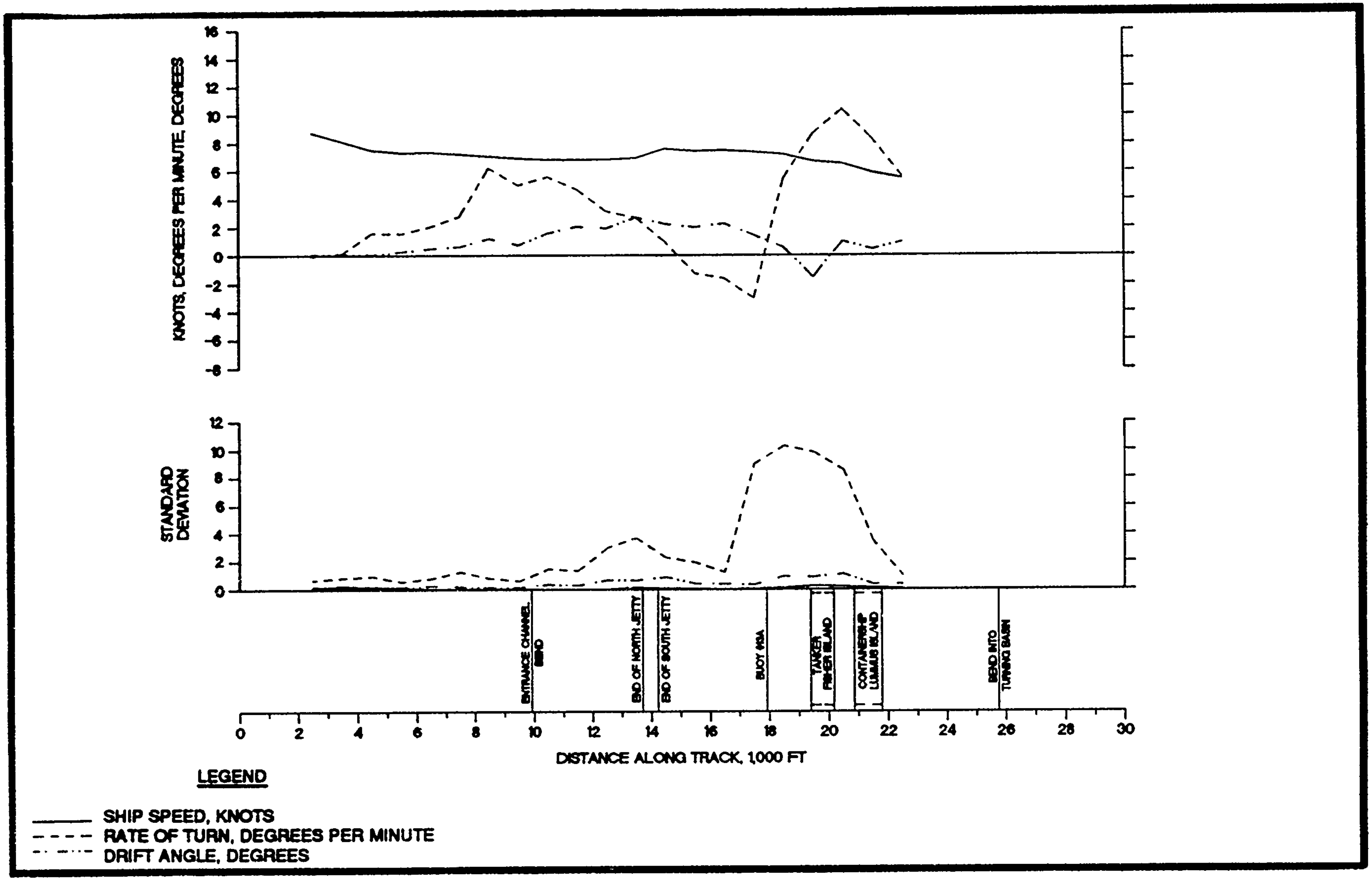


Figure 42. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot D

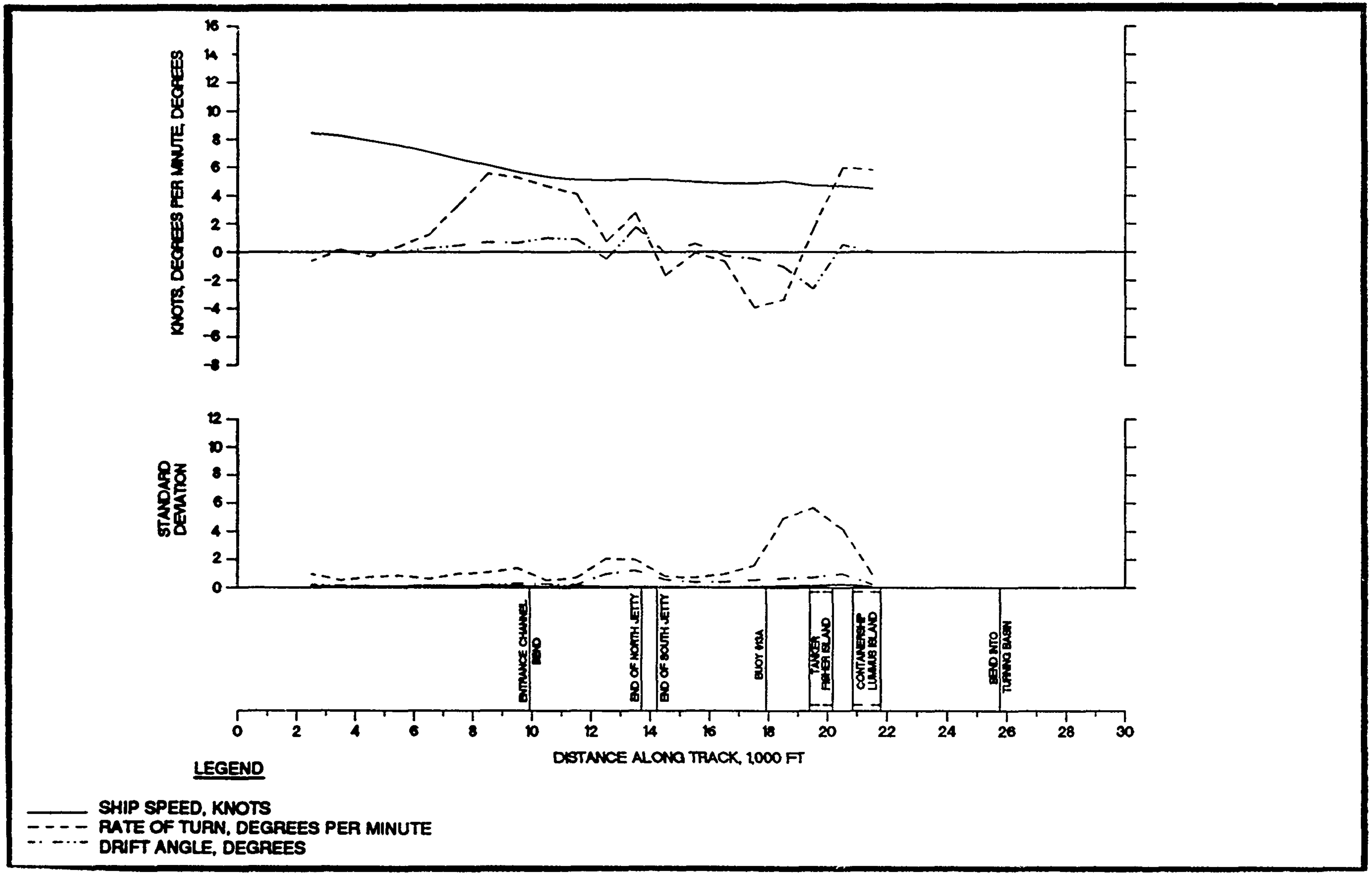


Figure 43. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, inbound, all runs

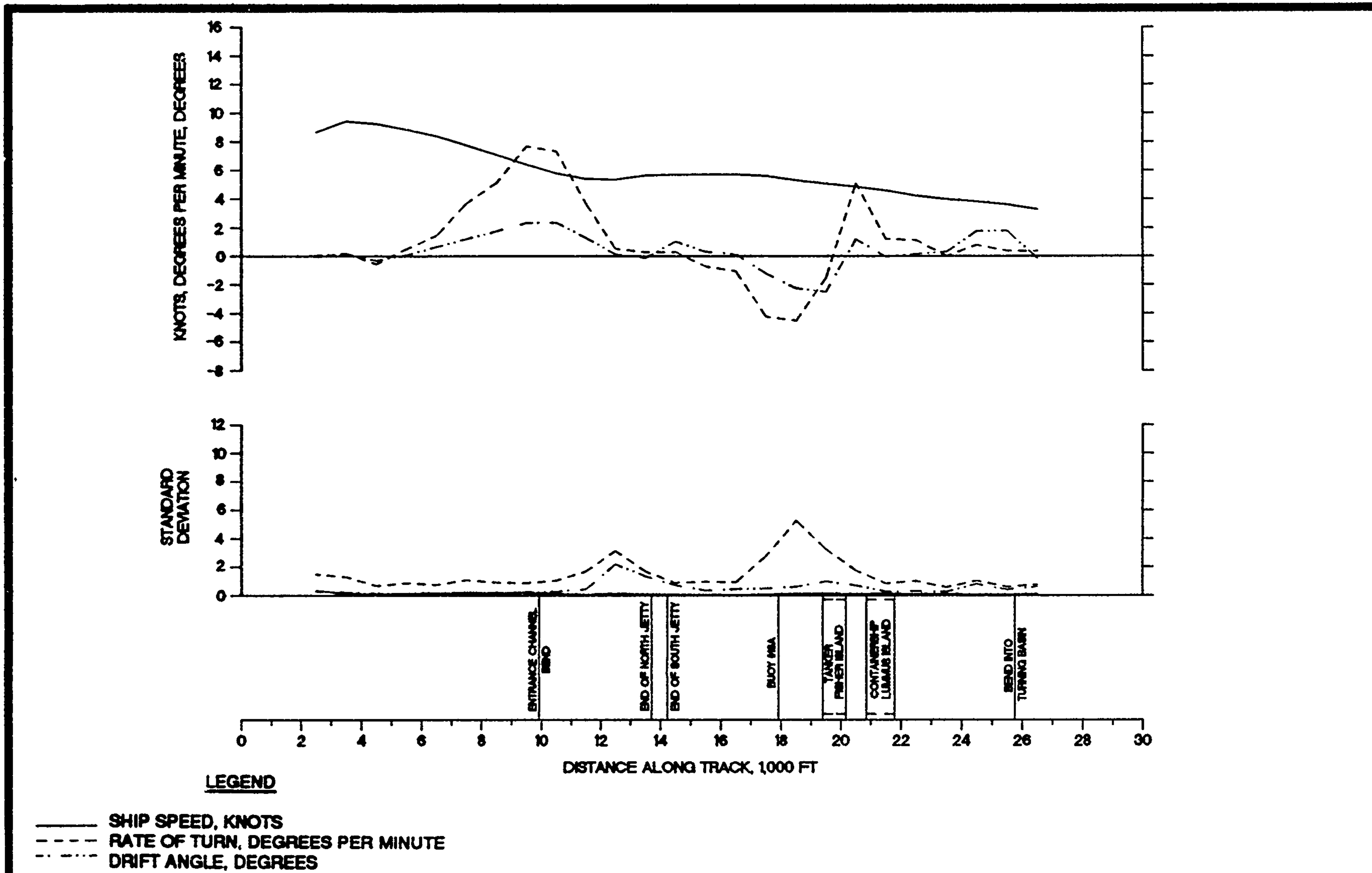


Figure 44. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, inbound with tugs, all runs

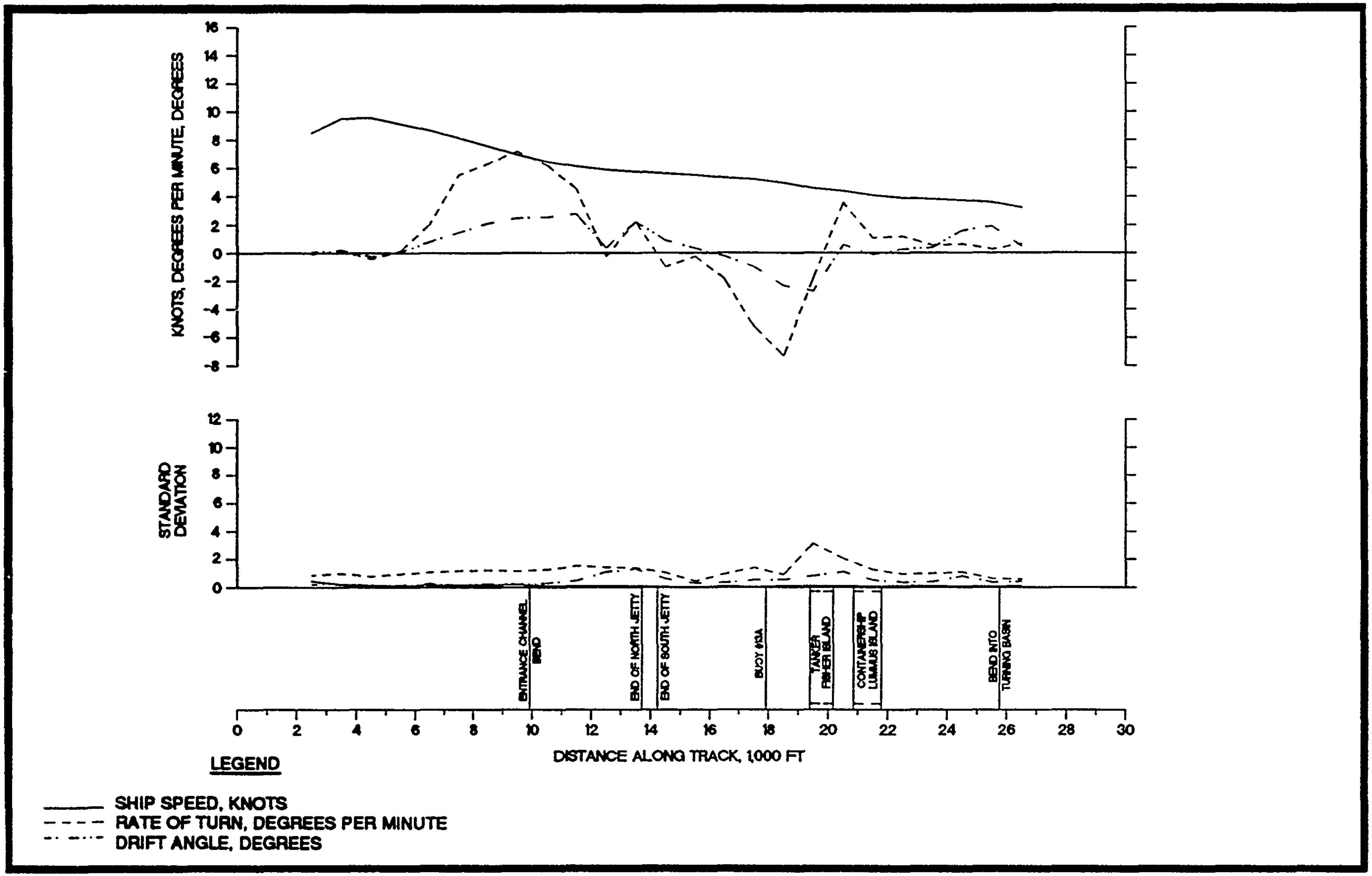


Figure 45. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, inbound with tugs, all runs

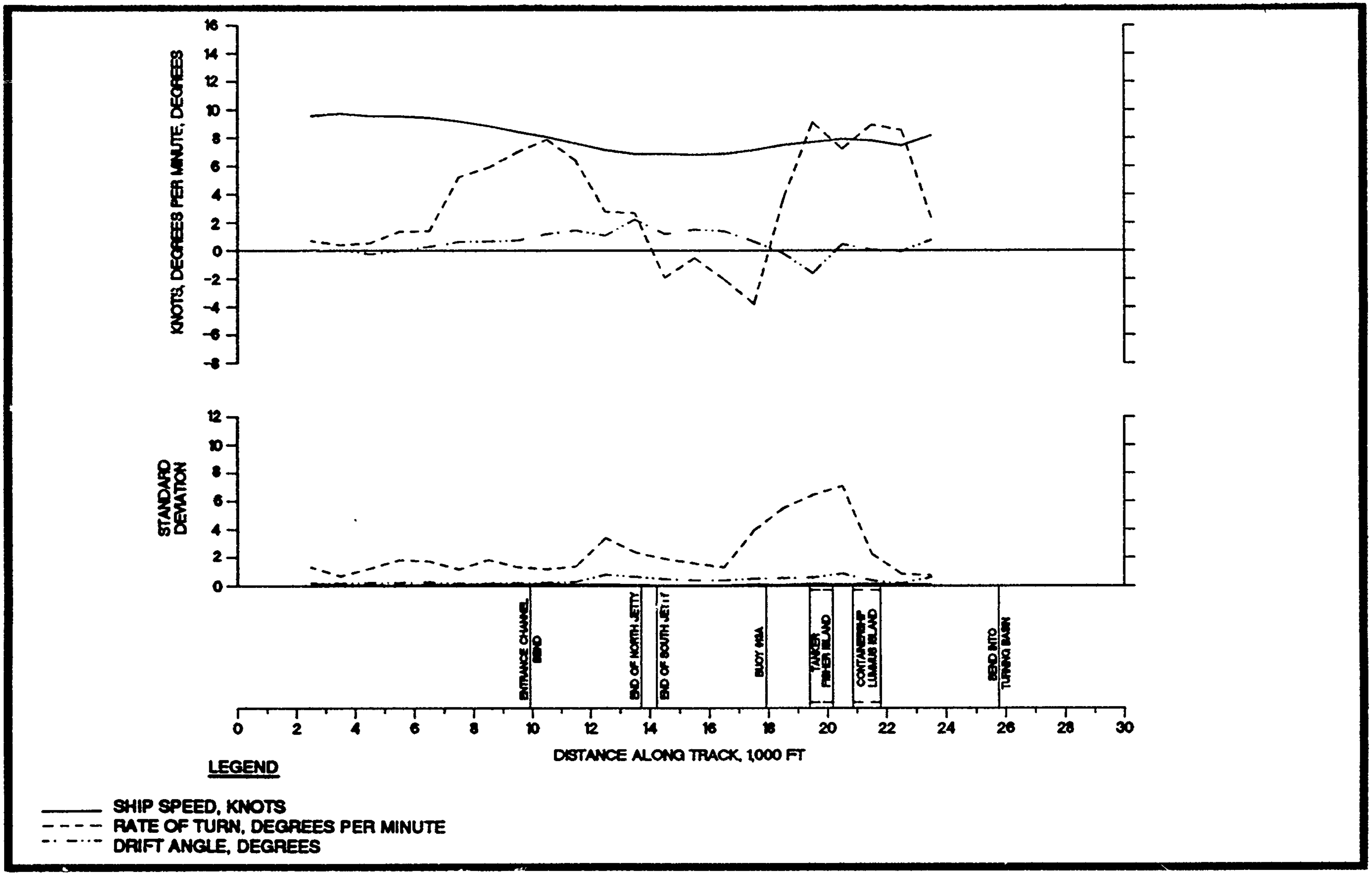


Figure 46. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, inbound, all runs

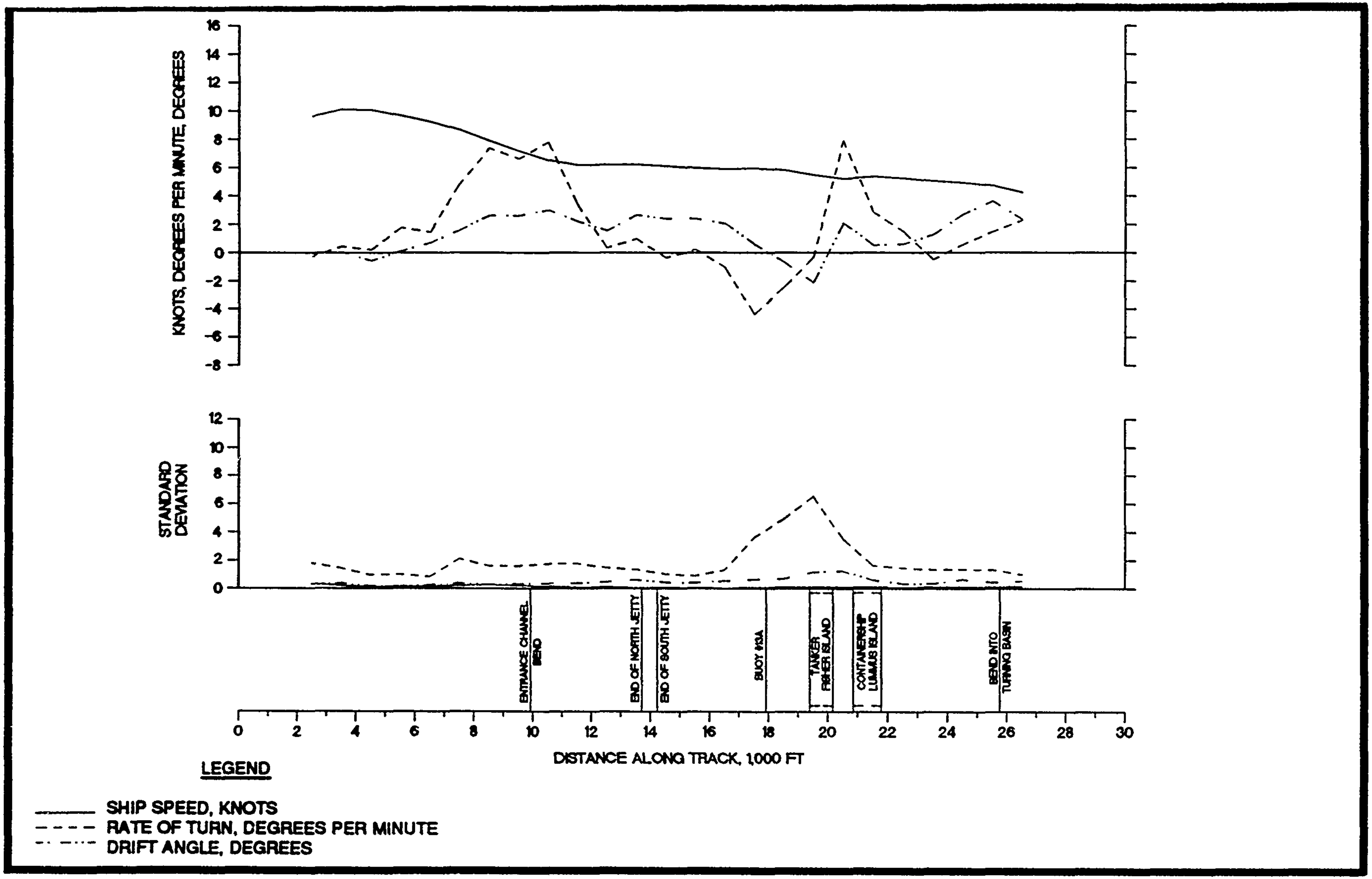


Figure 47. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

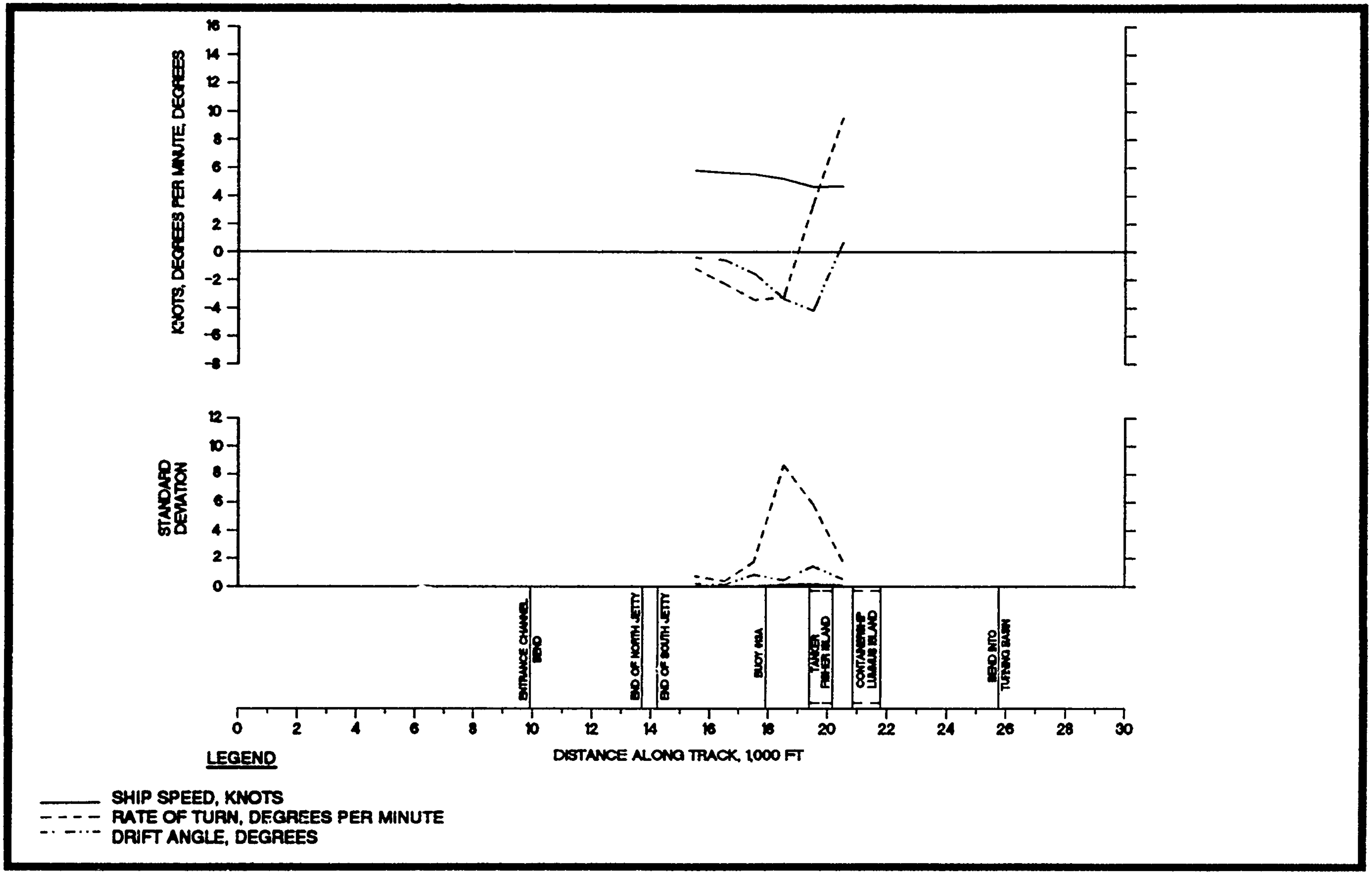


Figure 48. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot southeast wind, inbound, all runs

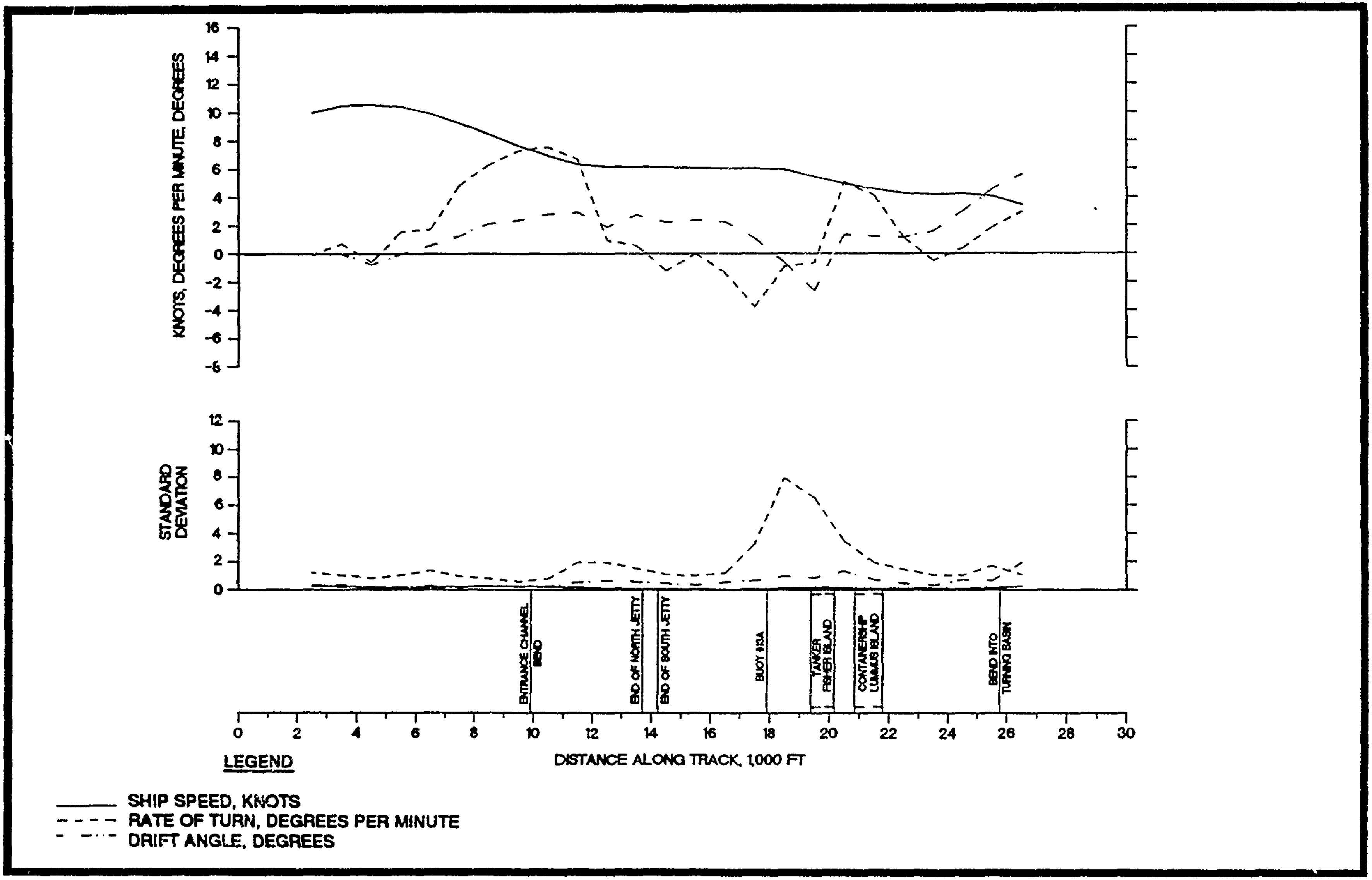


Figure 49. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

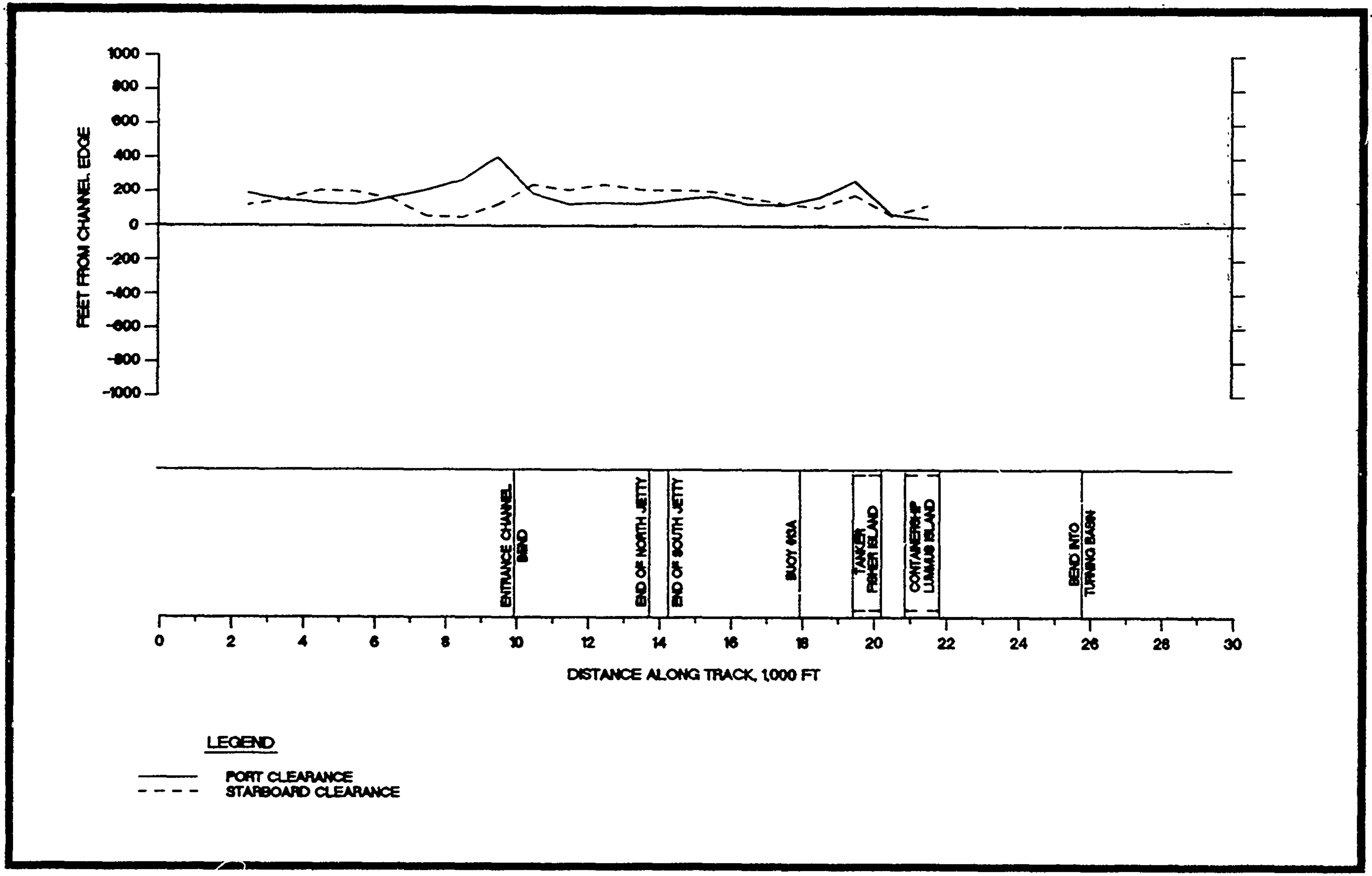


Figure 50. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot C

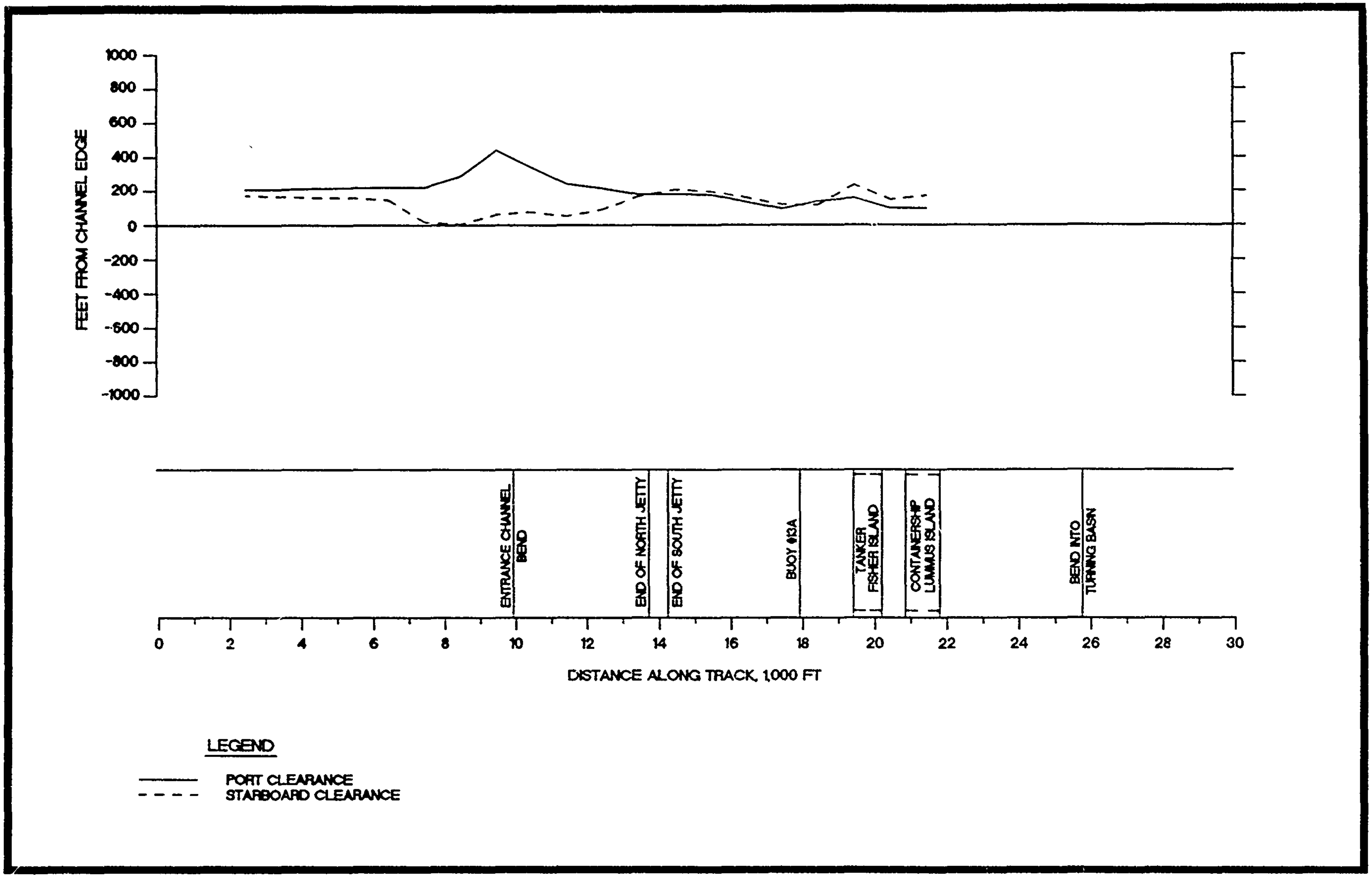


Figure 51. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, inbound, pilot D

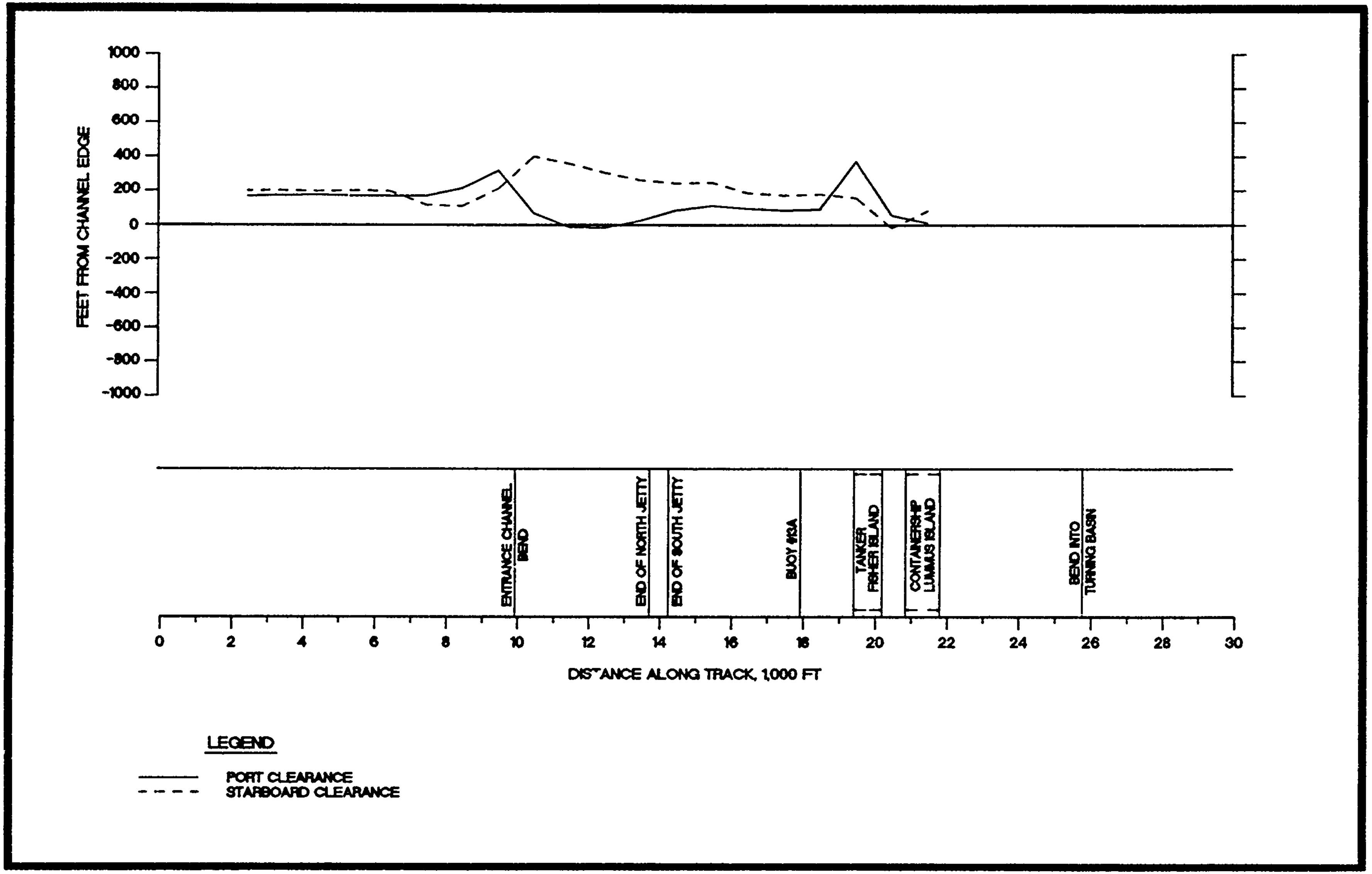


Figure 52. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot C

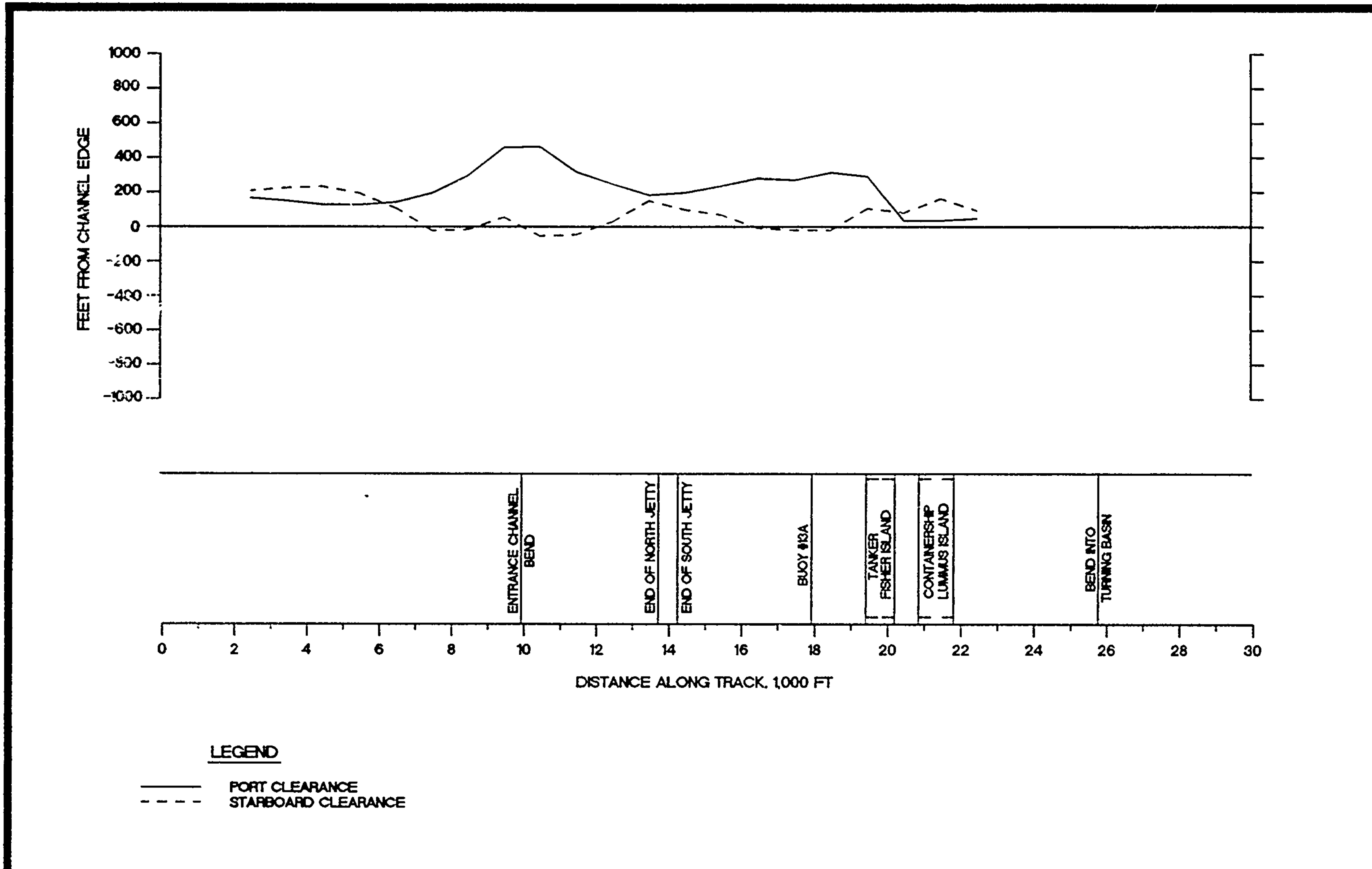


Figure 53. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, inbound, pilot D

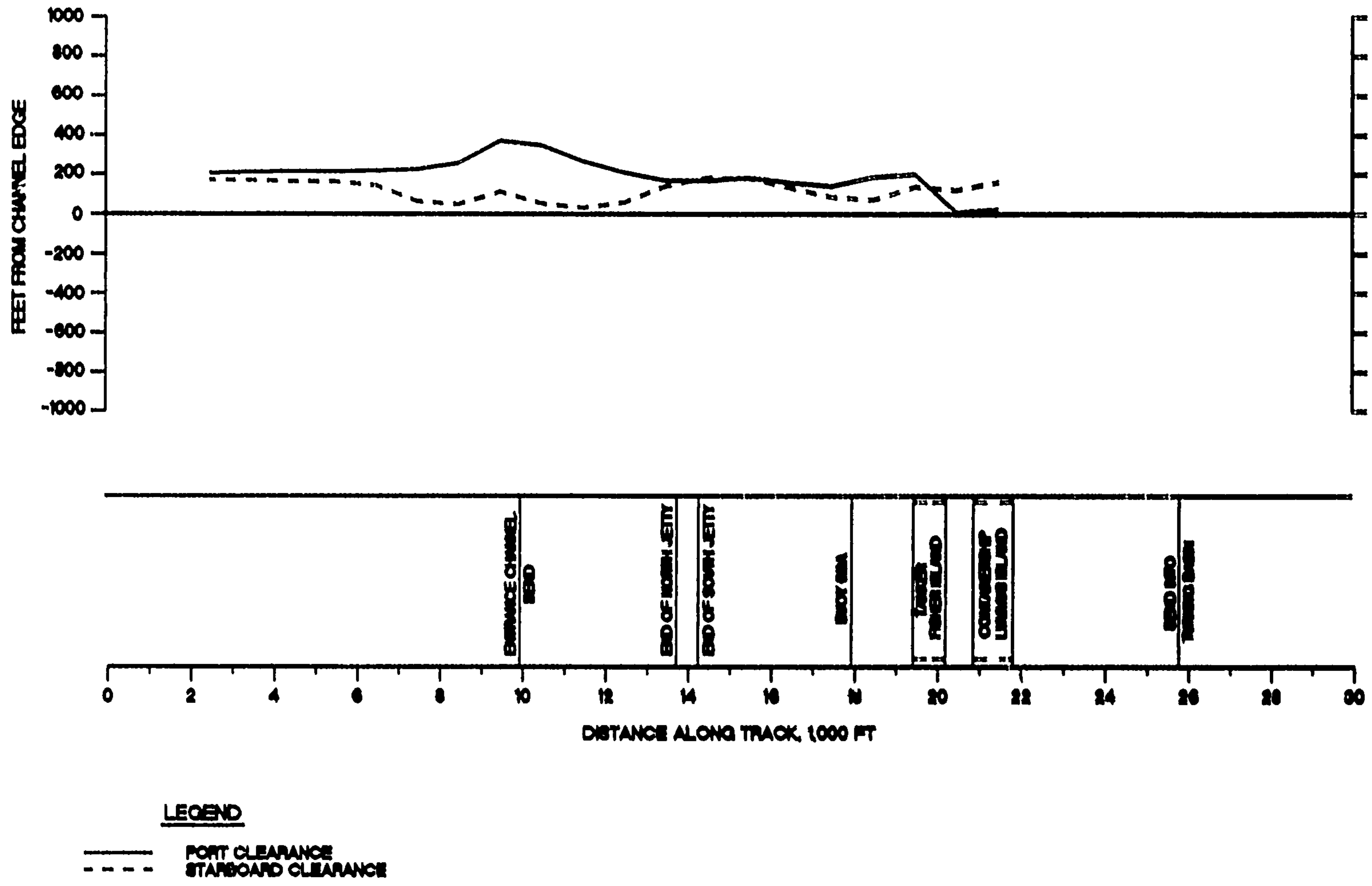


Figure 54. Port and starboard clearance, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, inbound, all runs

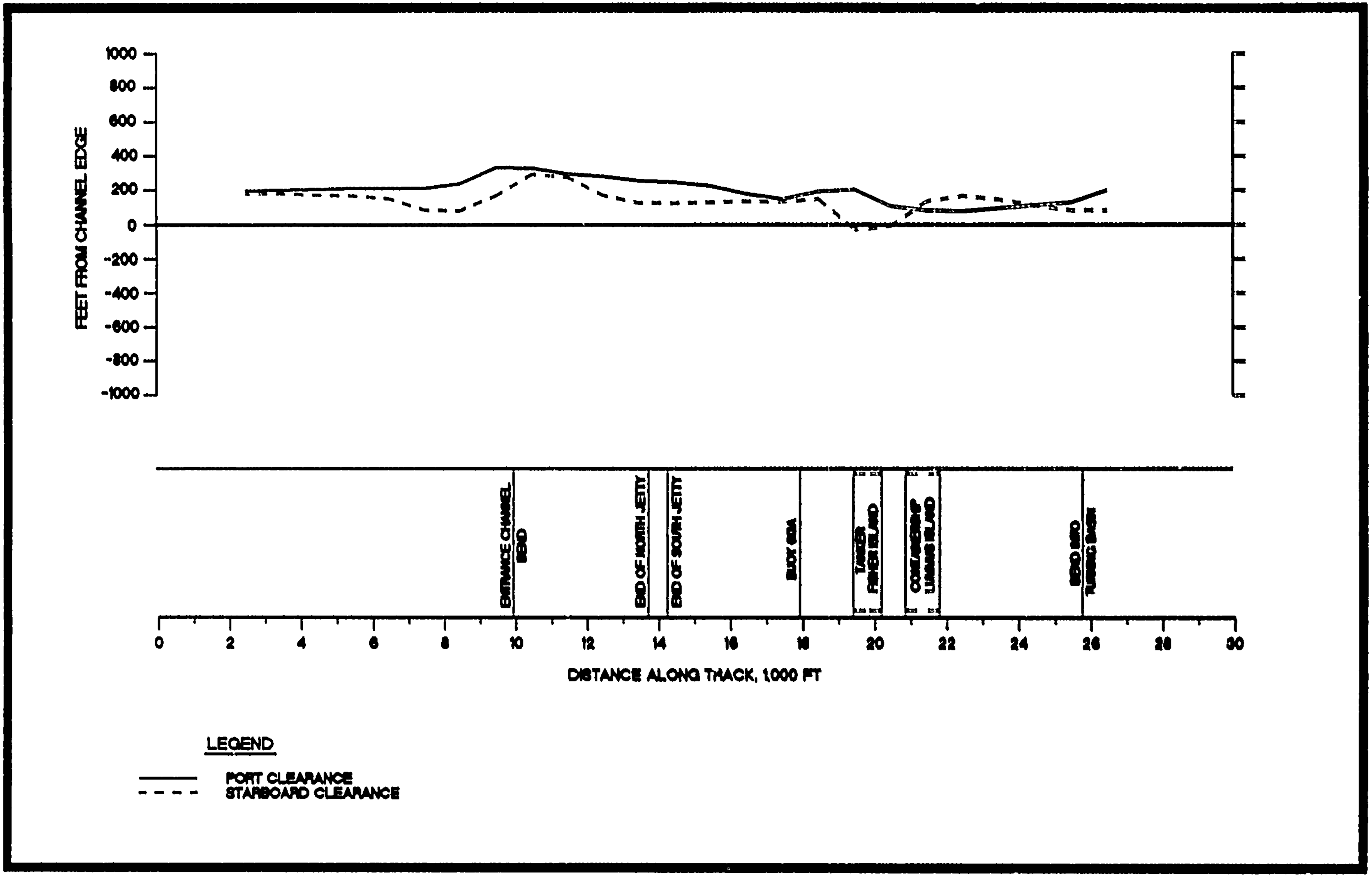


Figure 55. Port and starboard clearance, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, inbound with tugs, all runs

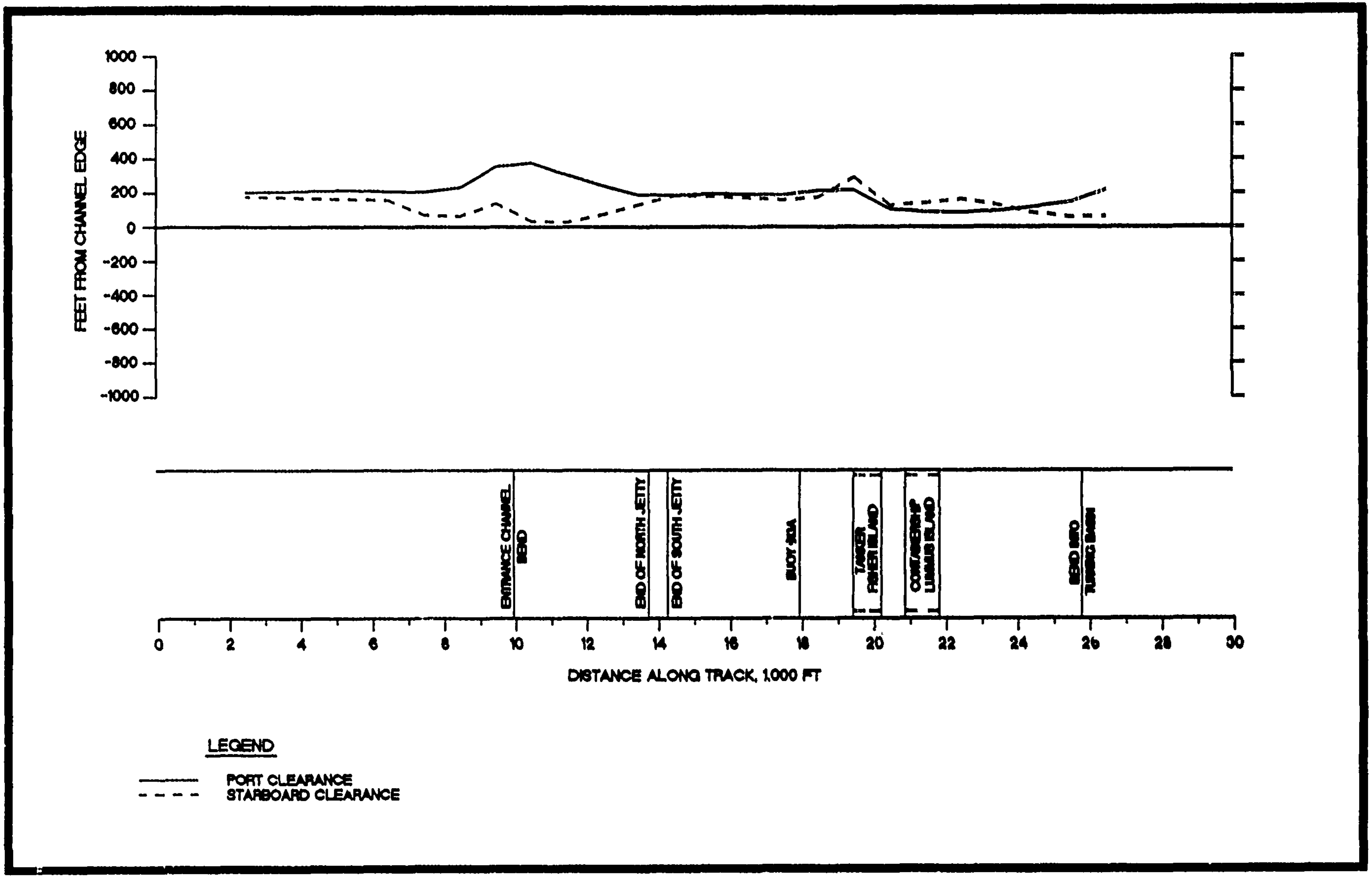


Figure 56. Port and starboard clearance, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, inbound with tugs, all runs

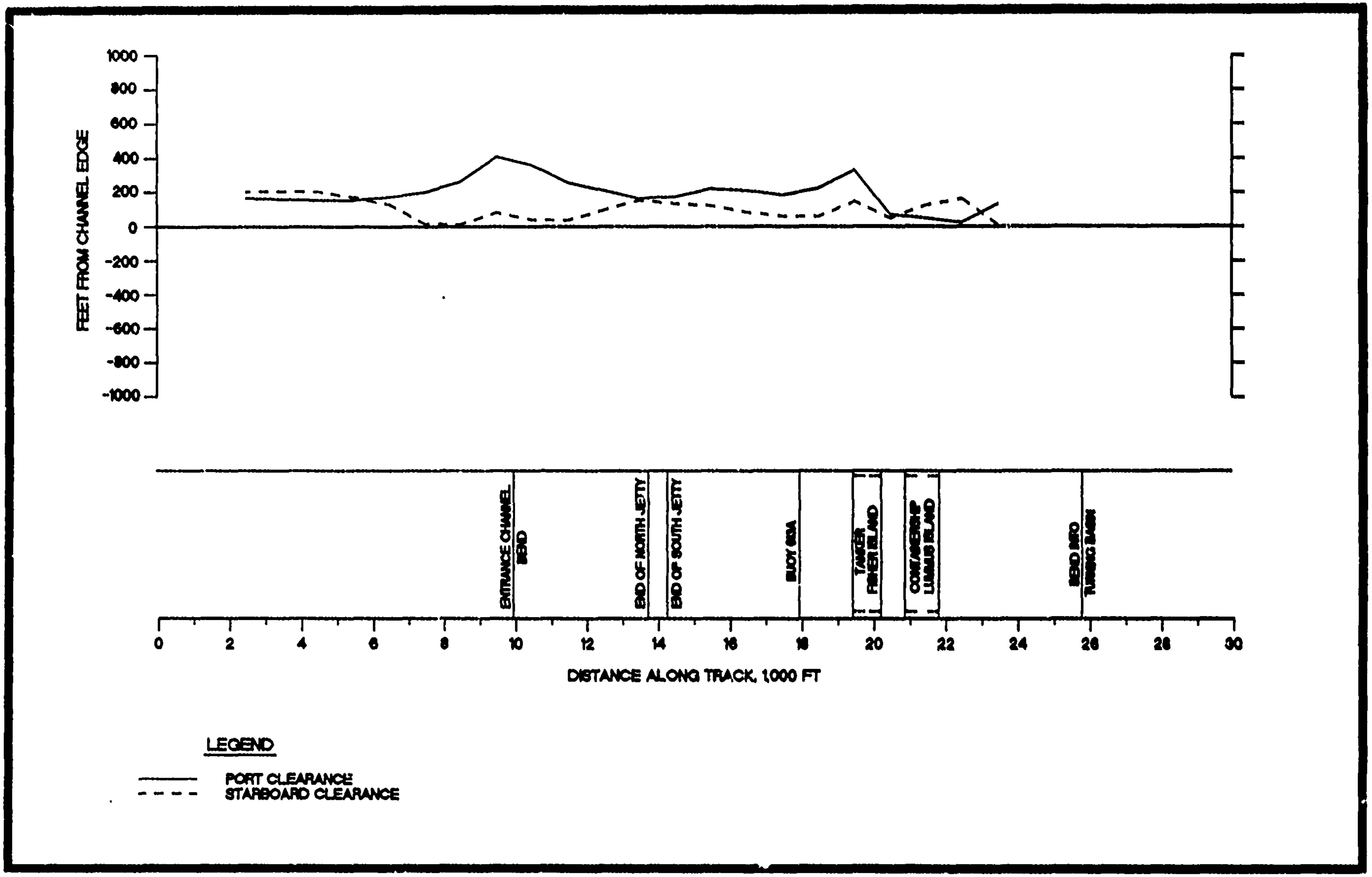


Figure 57. Port and starboard clearance, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, inbound, all runs

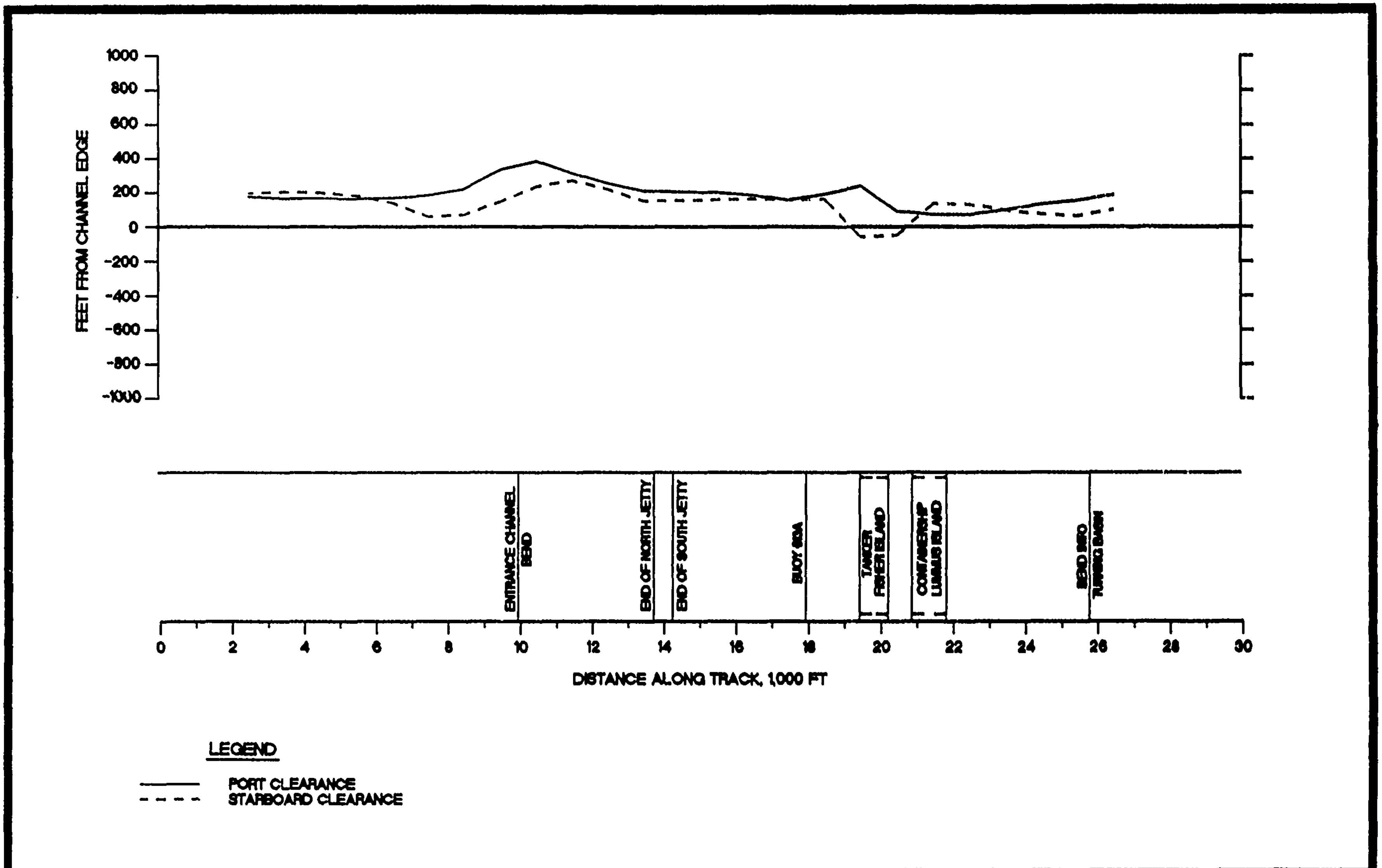


Figure 58. Port and starboard clearance, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

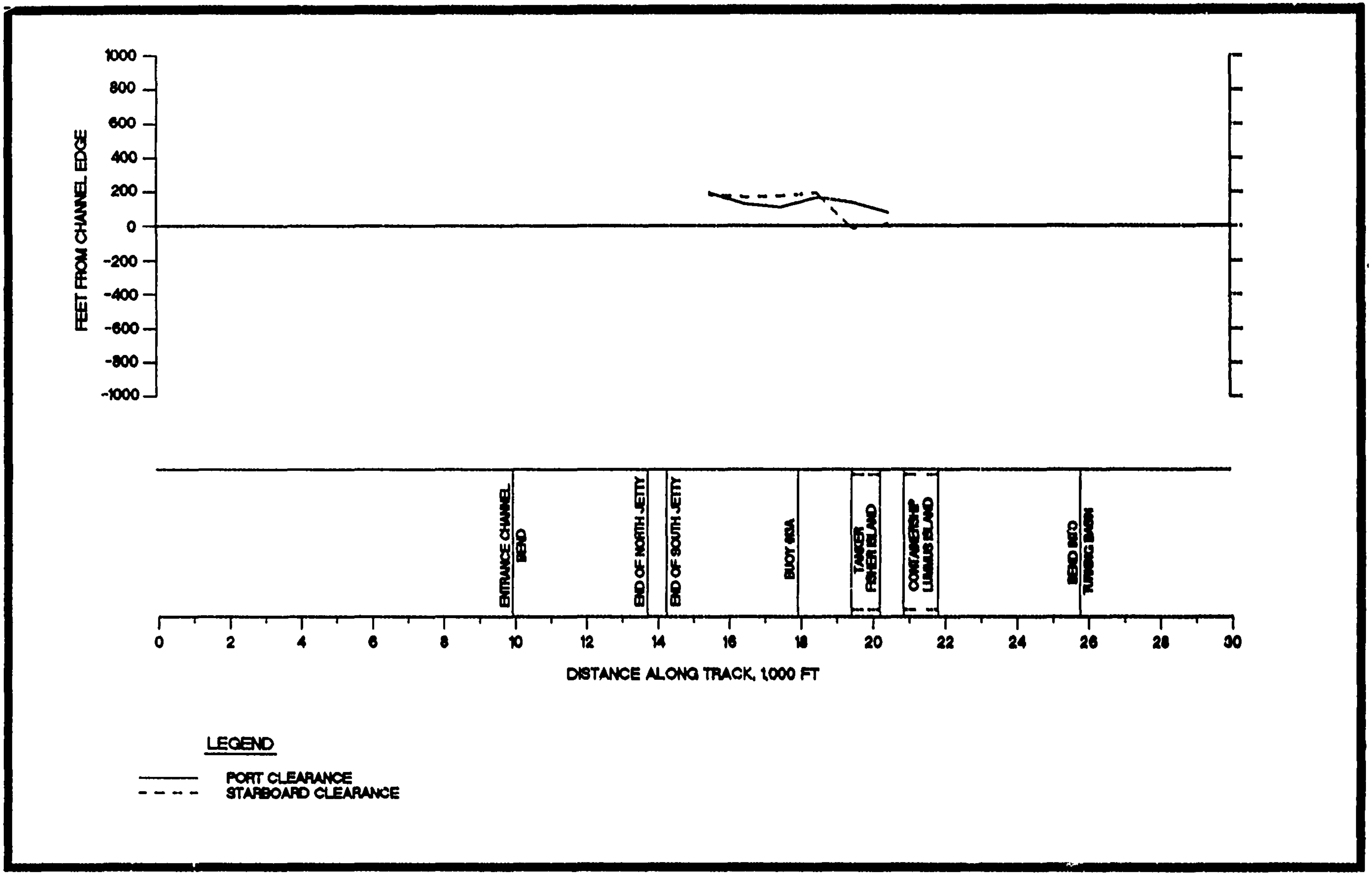


Figure 59. Port and starboard clearance, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot southeast wind, inbound, all runs

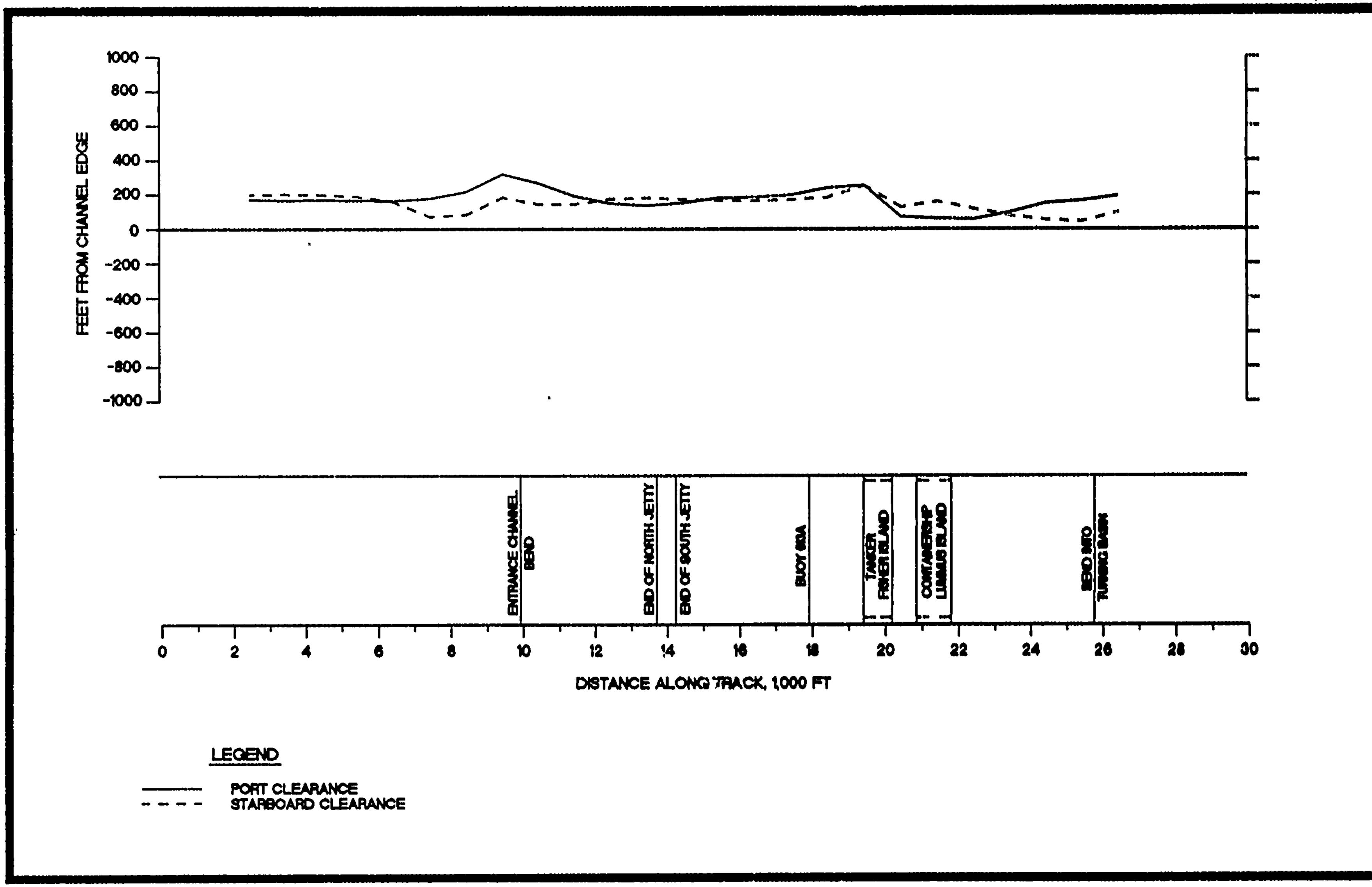


Figure 60. Port and starboard clearance, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, inbound with tugs, all runs

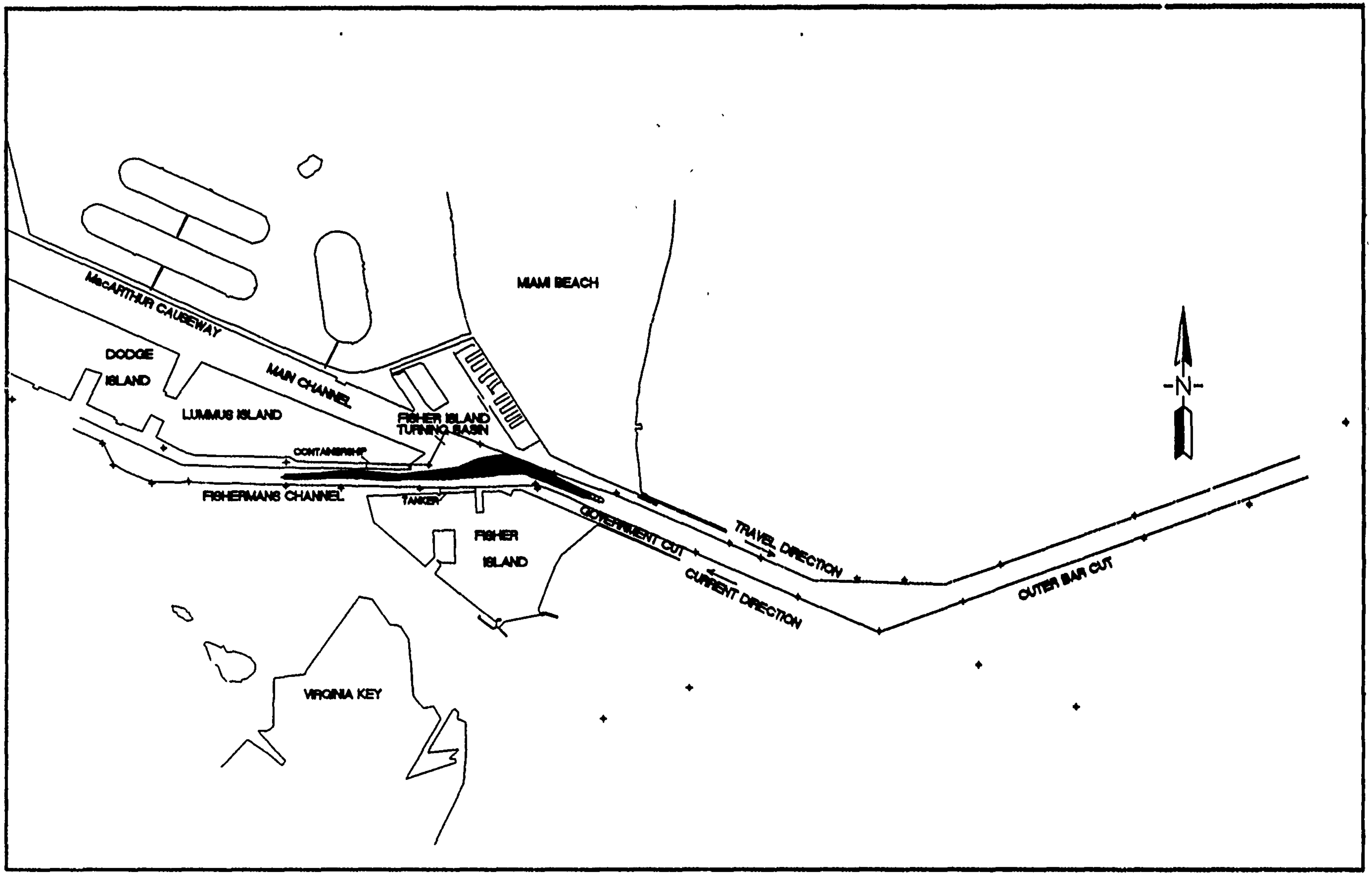


Figure 61. Composite track plots, existing channel, 860-ft containership, 34-ft draft, flood tide, outbound, all runs

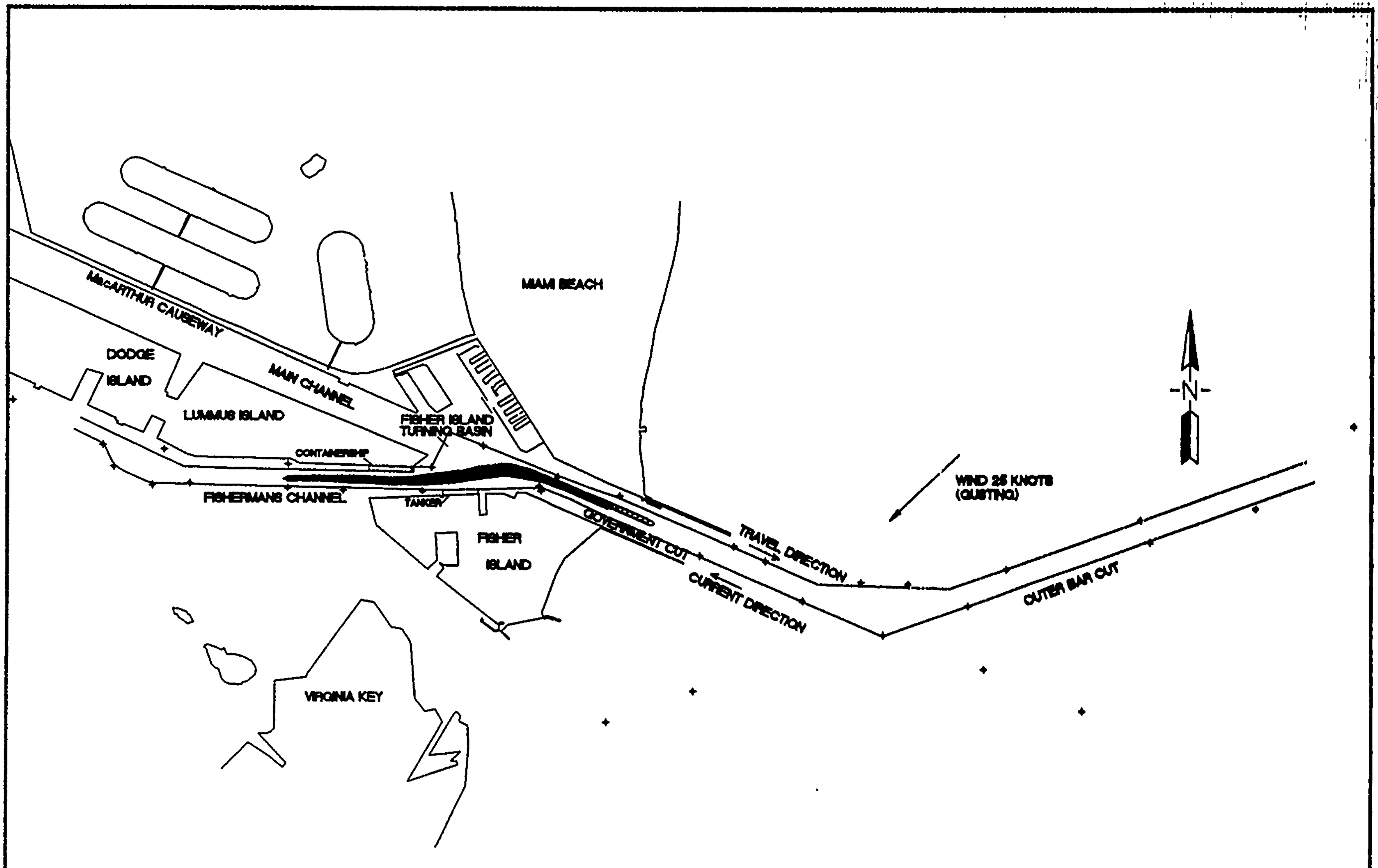


Figure 62. Composite track plots, existing channel, 860-ft containership, 34-ft draft, flood tide, 25-knot northeast wind, outbound, all runs

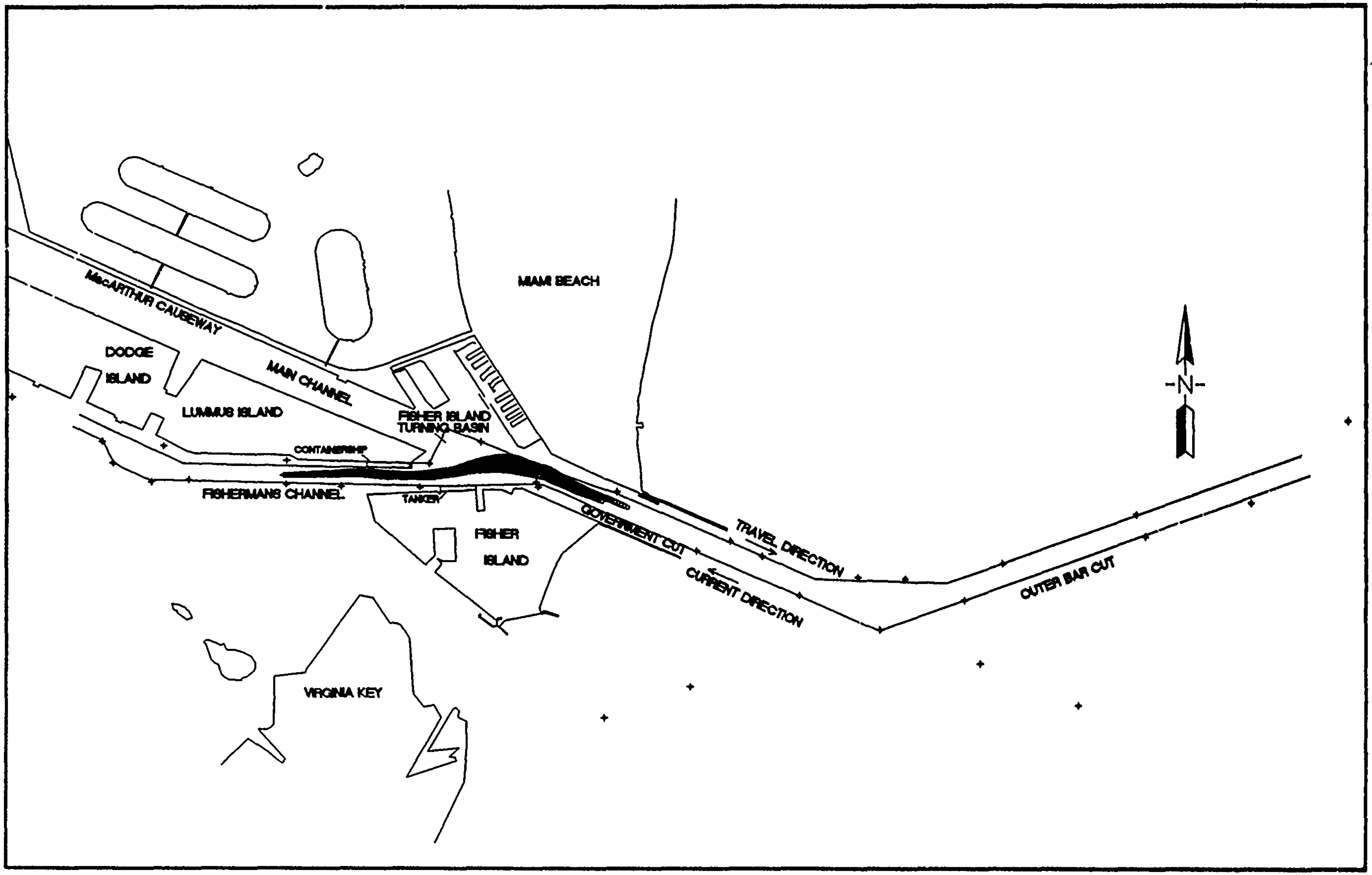


Figure 63. Composite track plots, existing channel, 950-ft containership, 34-ft draft, flood tide, outbound, all runs

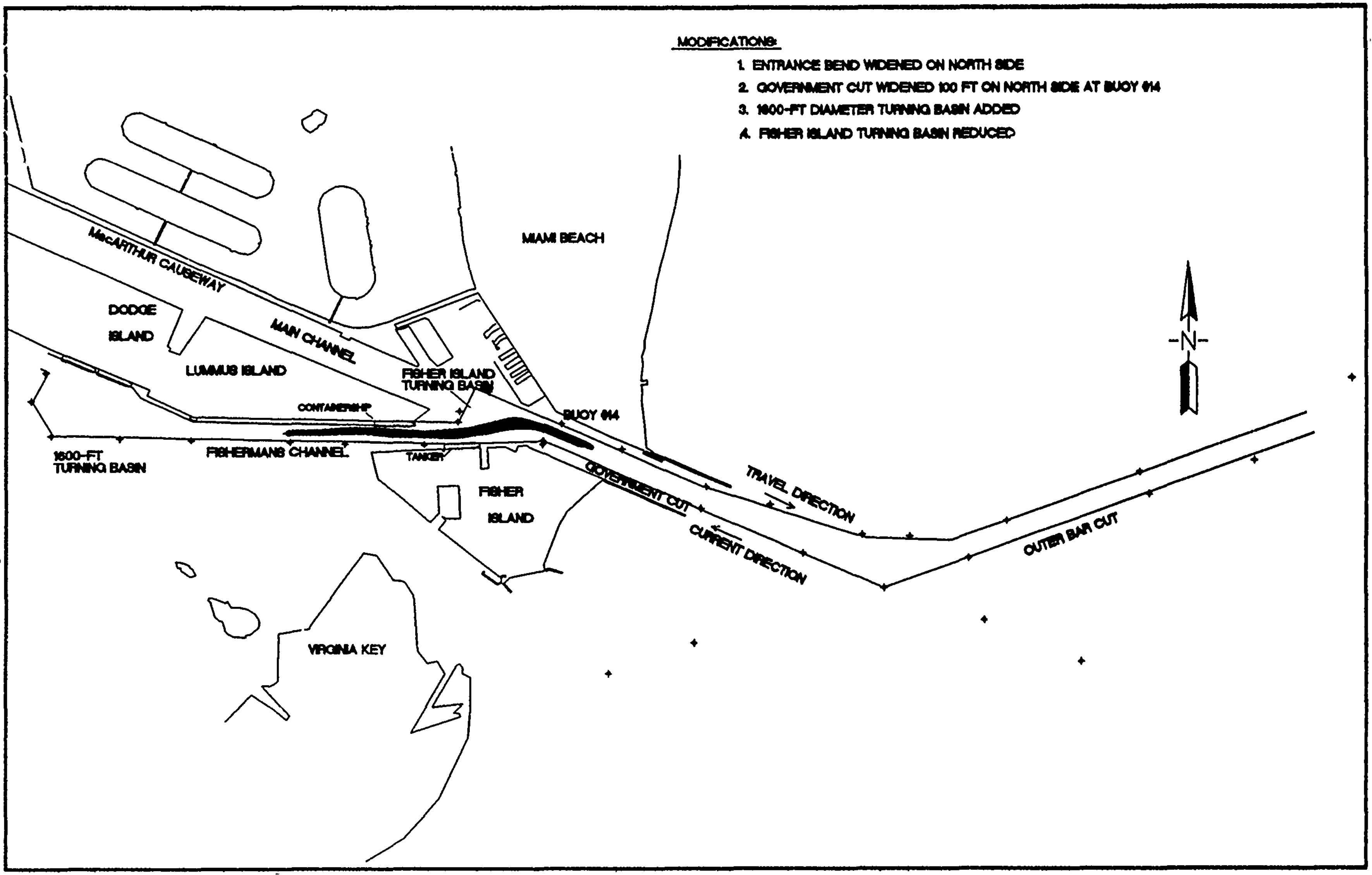


Figure 64. Composite track plots, proposed channel, 950-ft containership, 38-ft draft, flood tide, outbound, all runs

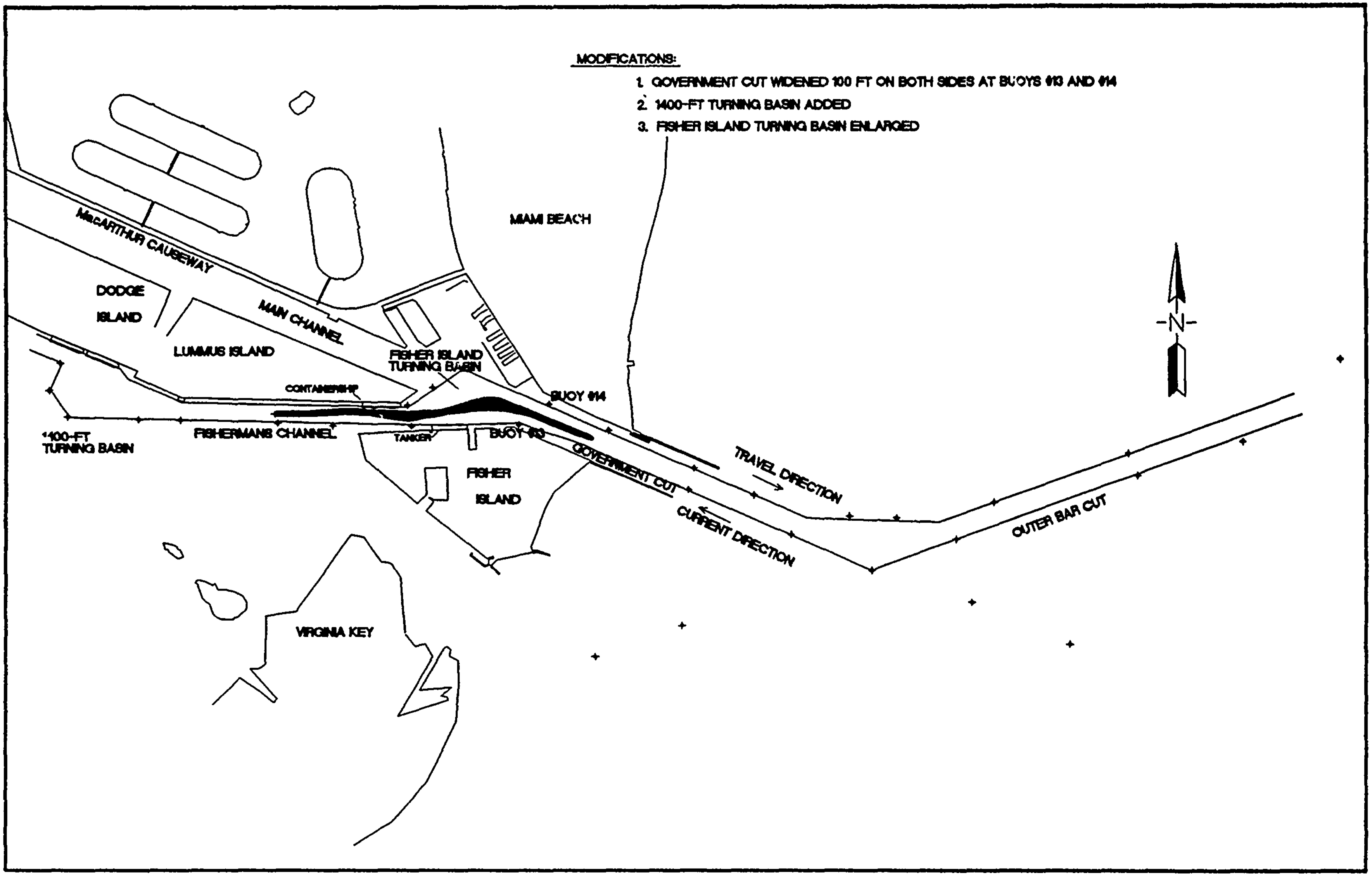


Figure 65. Composite track plots, alternative channel, 950-ft containership, 38-ft draft, flood tide, outbound, all runs

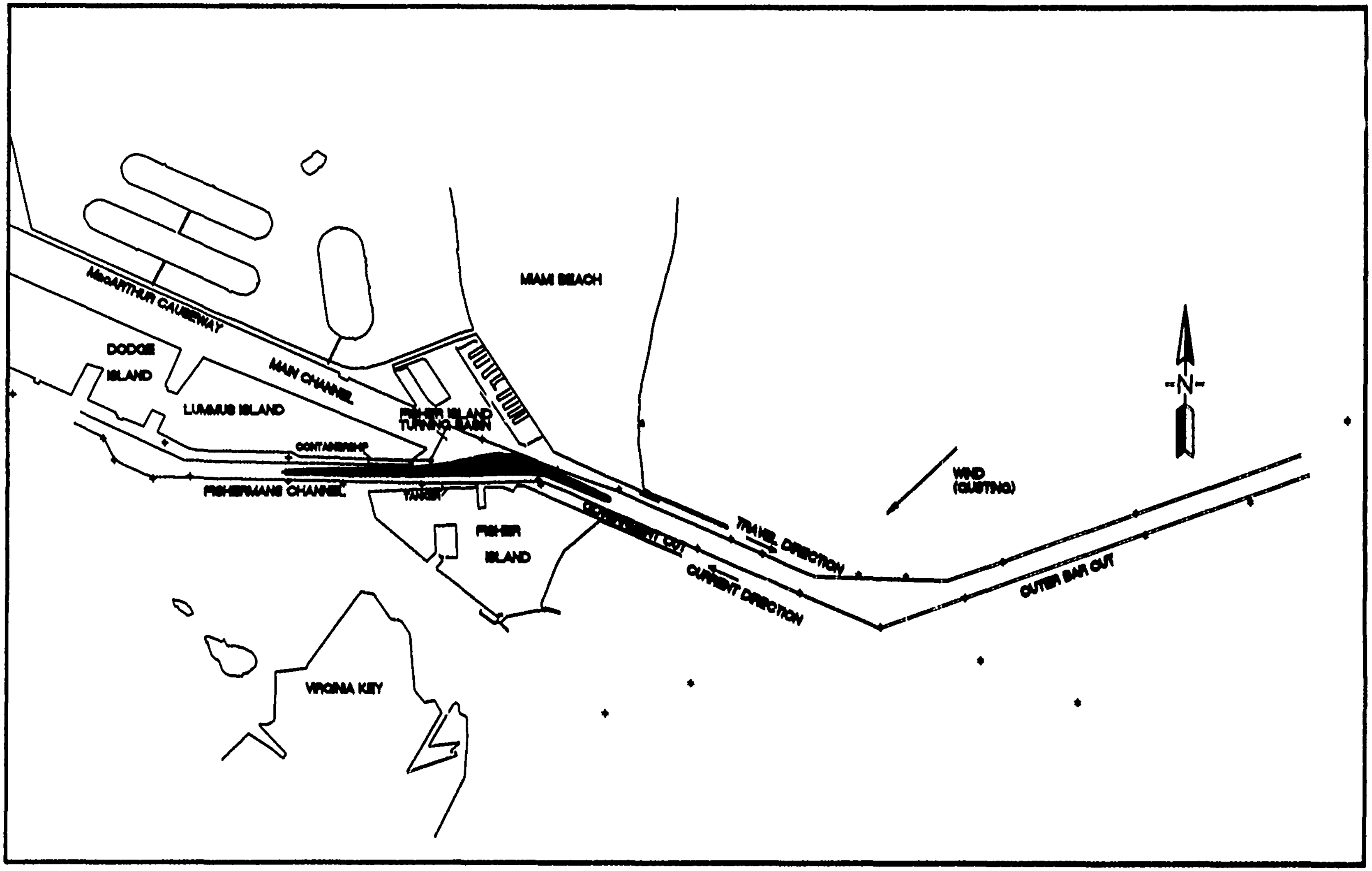


Figure 66. Composite track plots, existing channel, 950-ft containership, 34-ft draft, flood tide, with wind, outbound, all runs

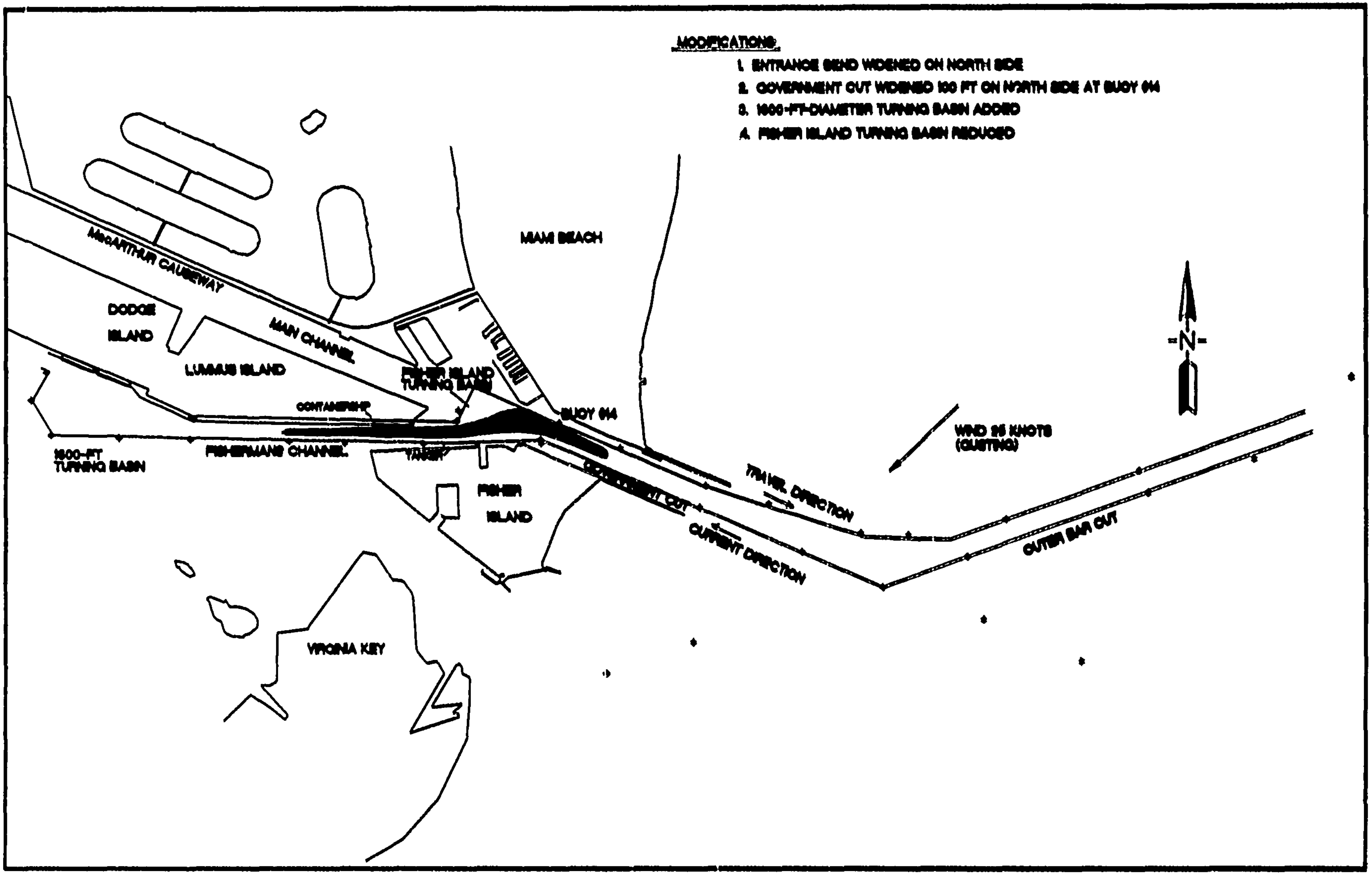


Figure 67. Composite track plots, proposed channel, 950-ft containership, 38-ft draft, flood tide, 25-knot northeast wind, outbound, all runs

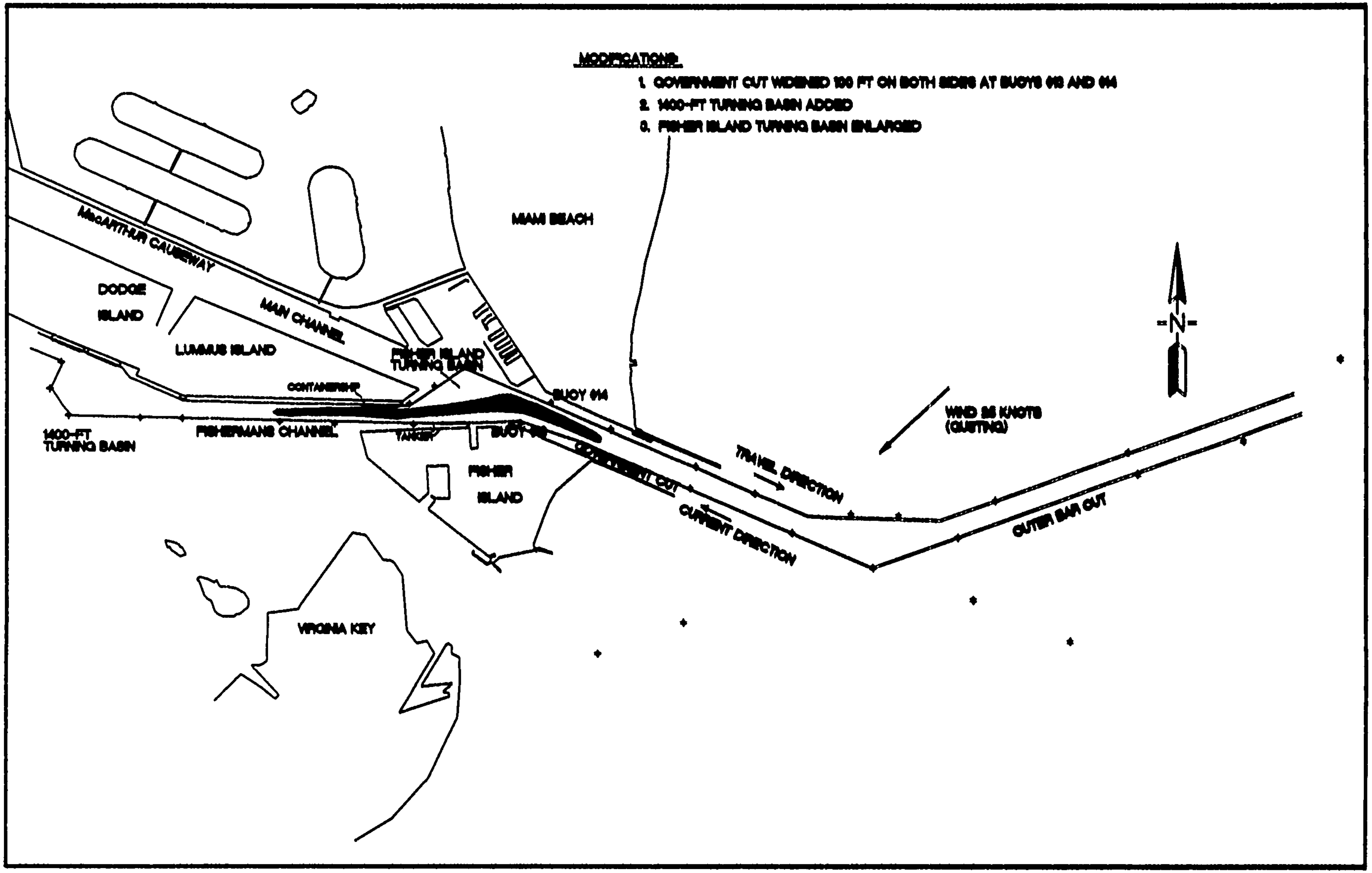


Figure 68. Composite track plots, alternative channel, 950-ft containership, 38-ft draft, flood tide, 25-knot northeast wind, outbound, all runs

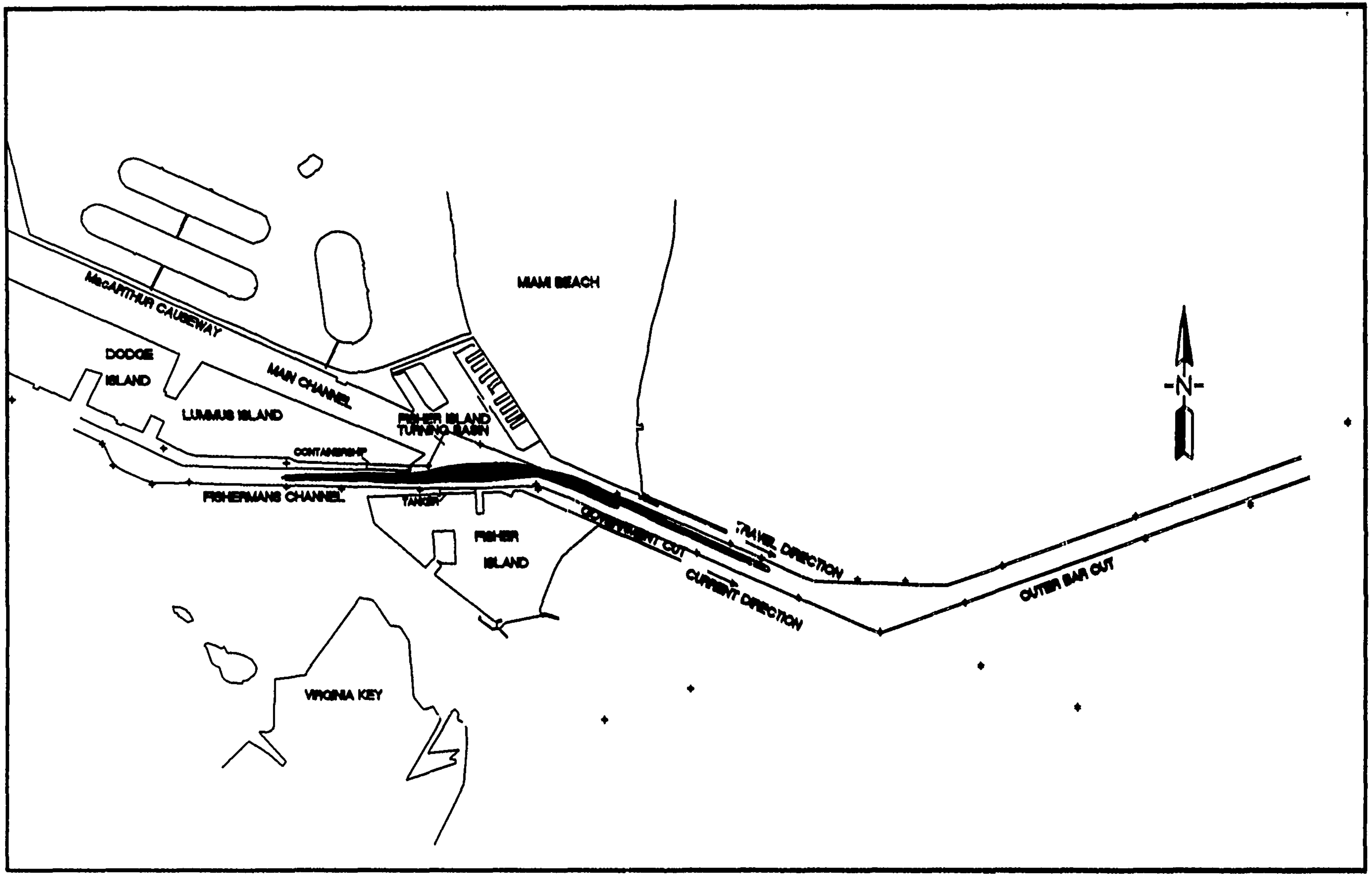


Figure 69. Composite track plots, existing channel, 860-ft containership, 34-ft draft, ebb tide, outbound, all runs

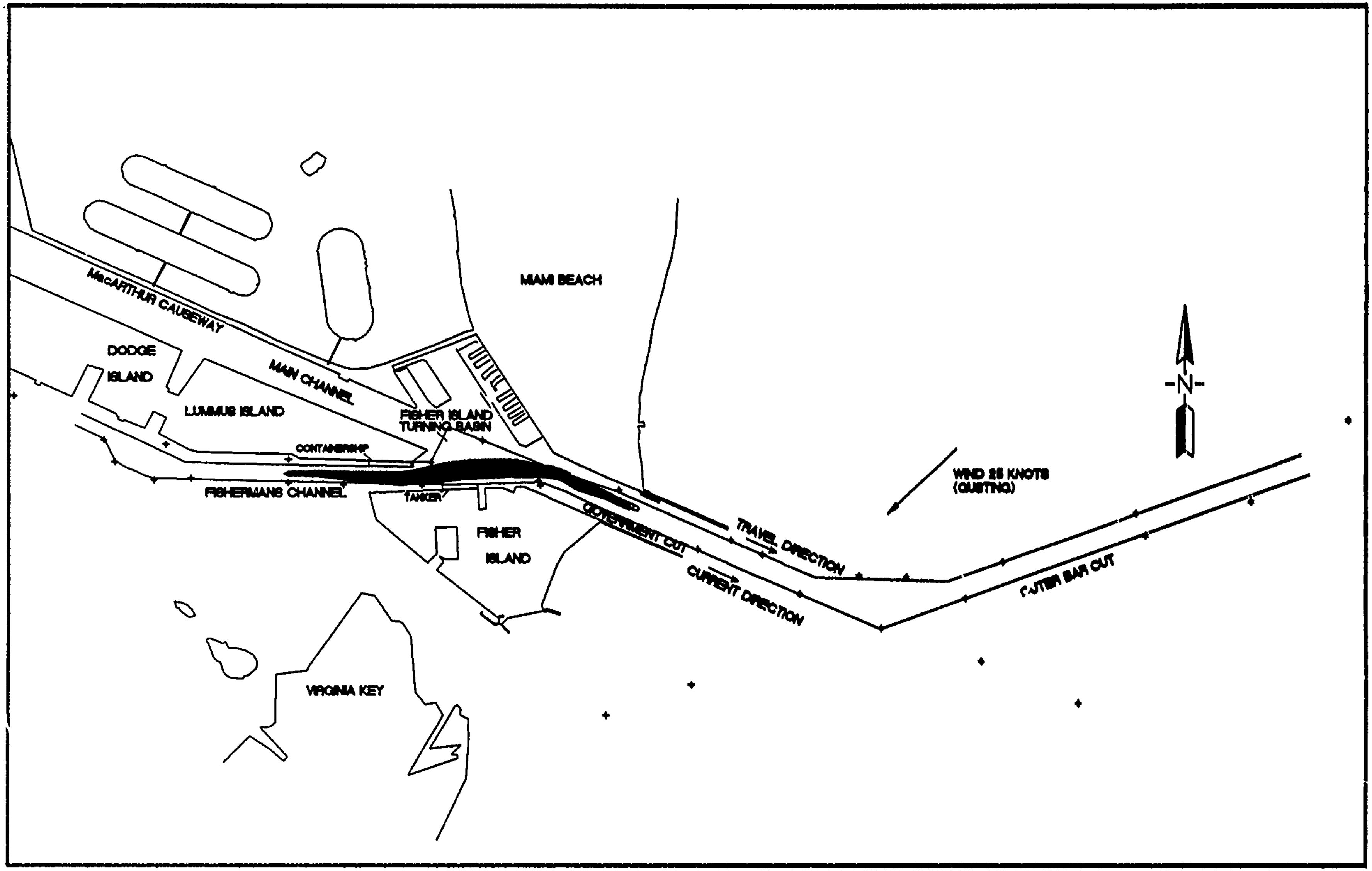


Figure 70. Composite track plots, existing channel, 860-ft containership, 34-ft draft, ebb tide, 25-knot northeast wind, outbound, all runs

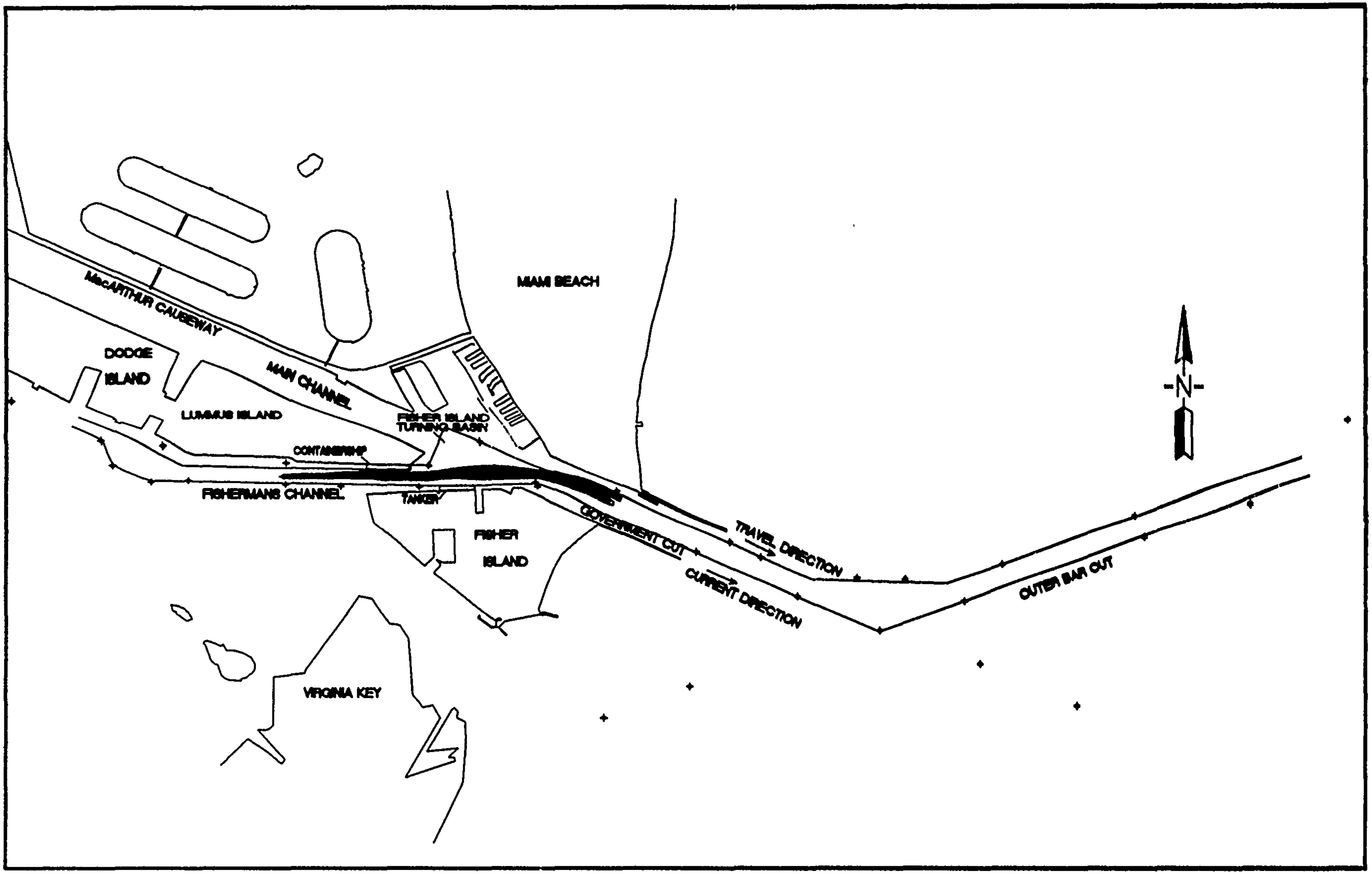


Figure 71. Composite track plots, existing channel, 950-ft containership, 34-ft draft, ebb tide, outbound, all runs

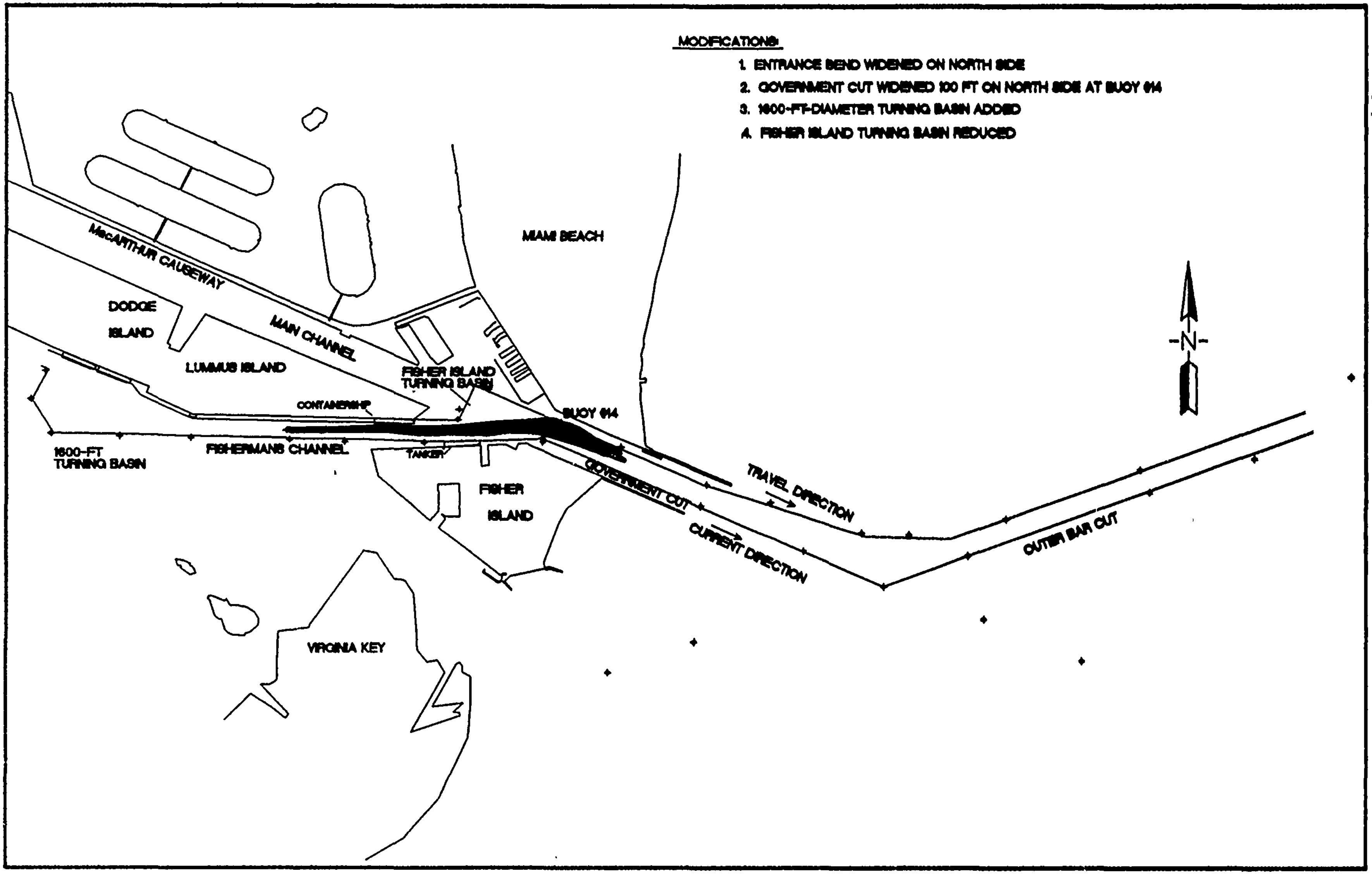


Figure 72. Composite track plots, proposed channel, 950-ft containership, 38-ft draft, ebb tide, outbound, all runs

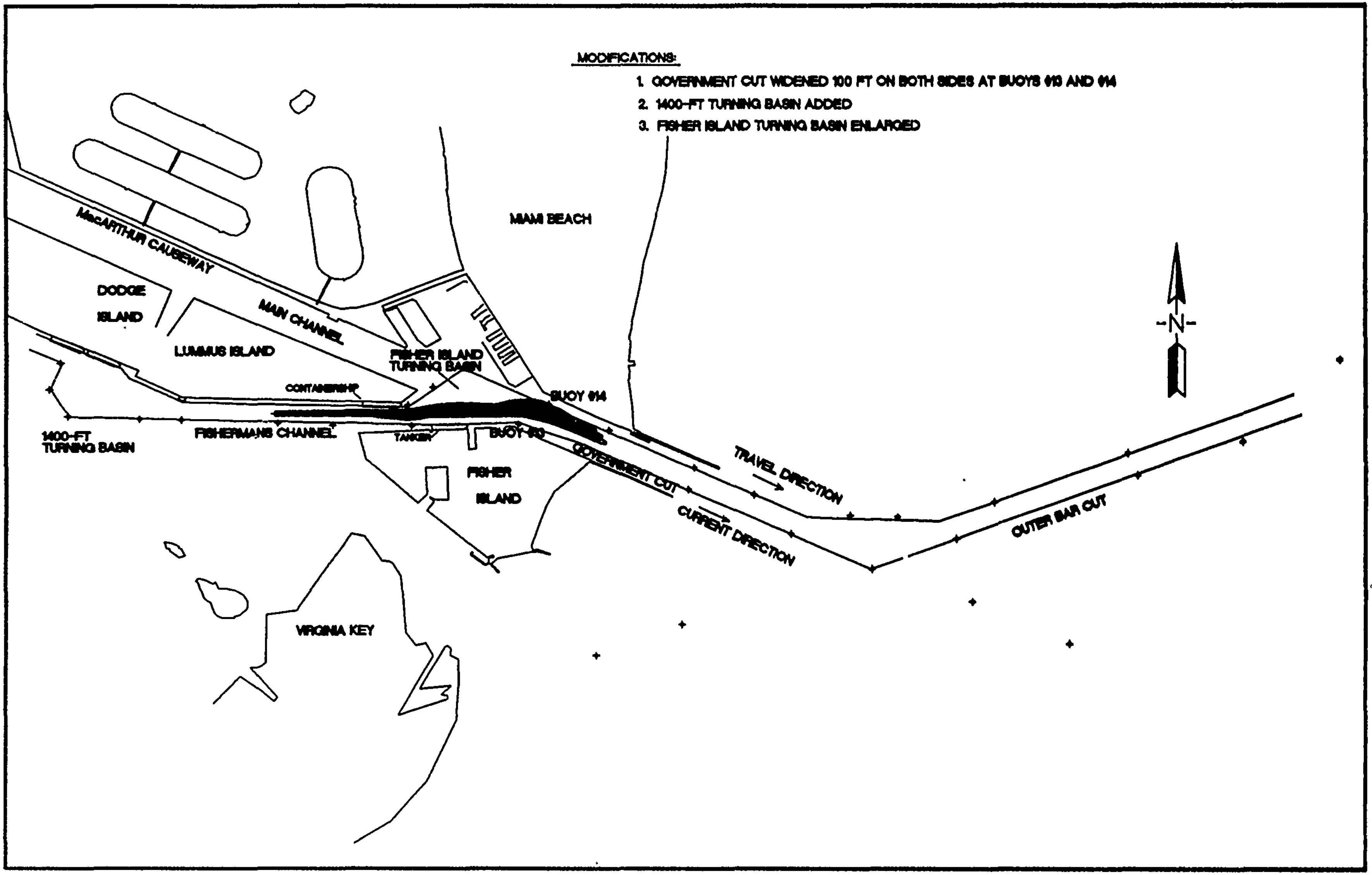


Figure 73. Composite track plots, alternative channel, 950-ft containership, 38-ft draft, ebb tide, outbound, all runs

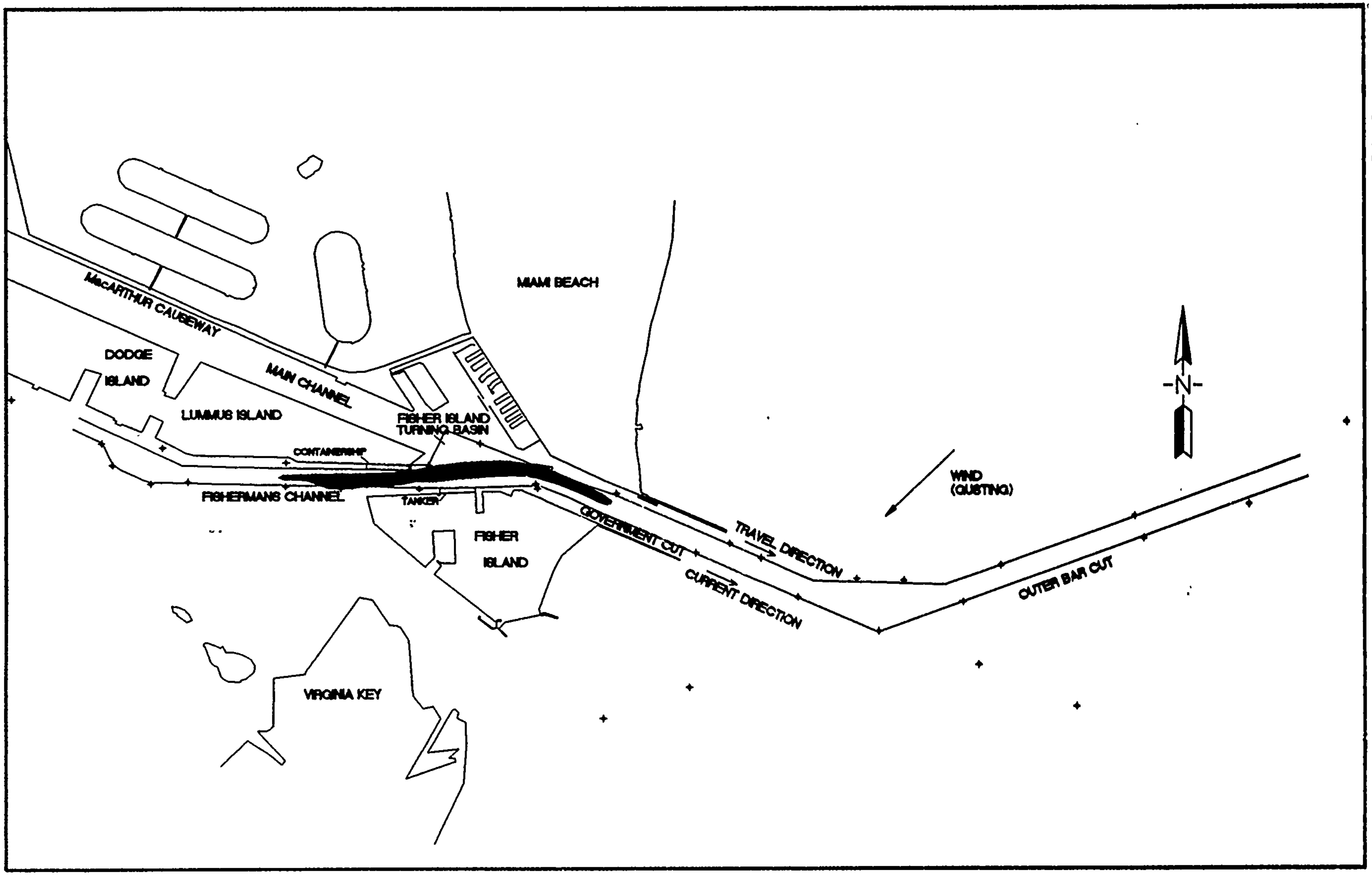


Figure 74. Composite track plots, existing channel, 950-ft containership, 34-ft draft, ebb tide, with wind, outbound, all runs

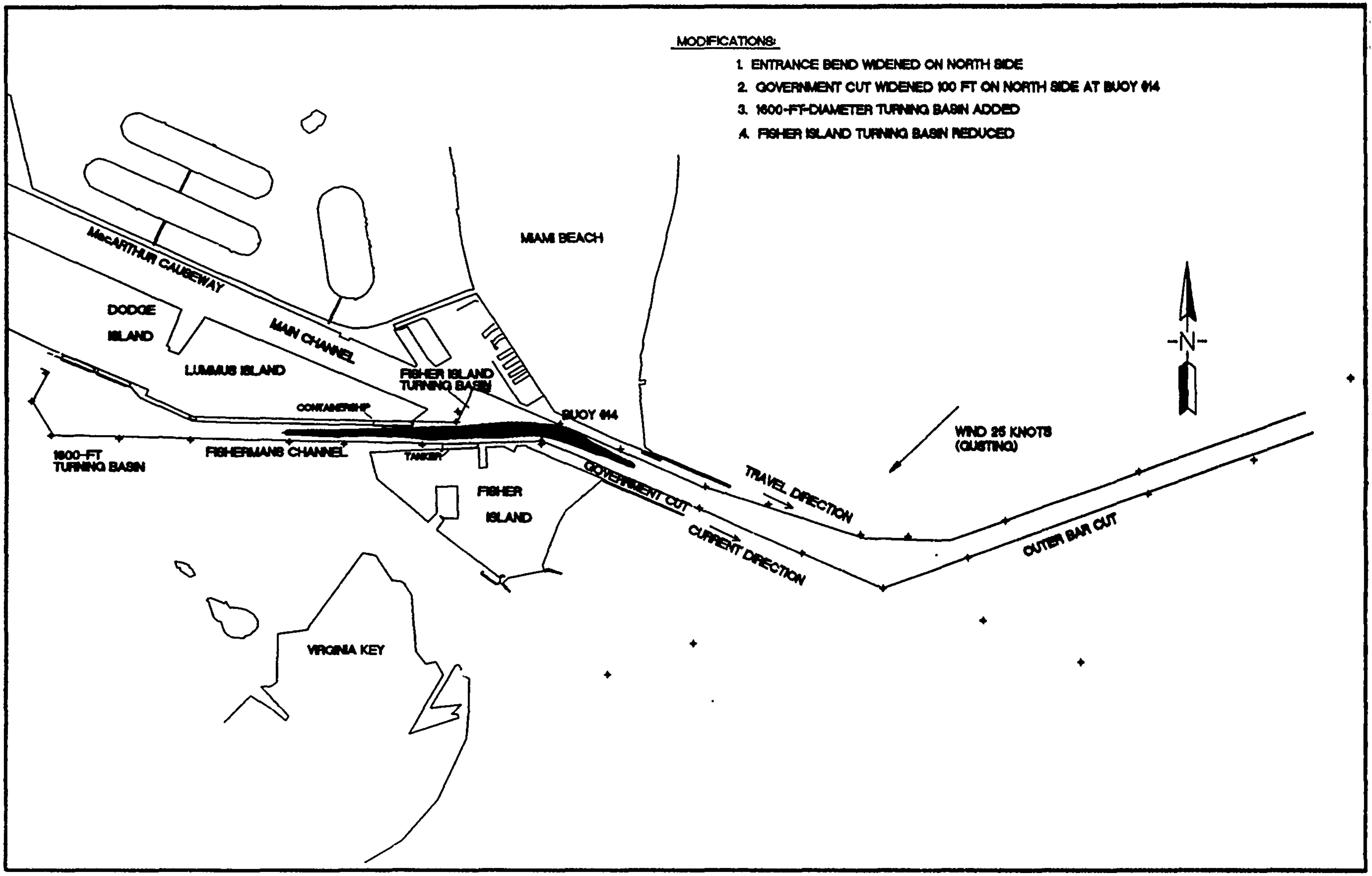


Figure 75. Composite track plots, proposed channel, 950-ft containership, 38-ft draft, ebb tide, 25-knot northeast wind, outbound, all runs

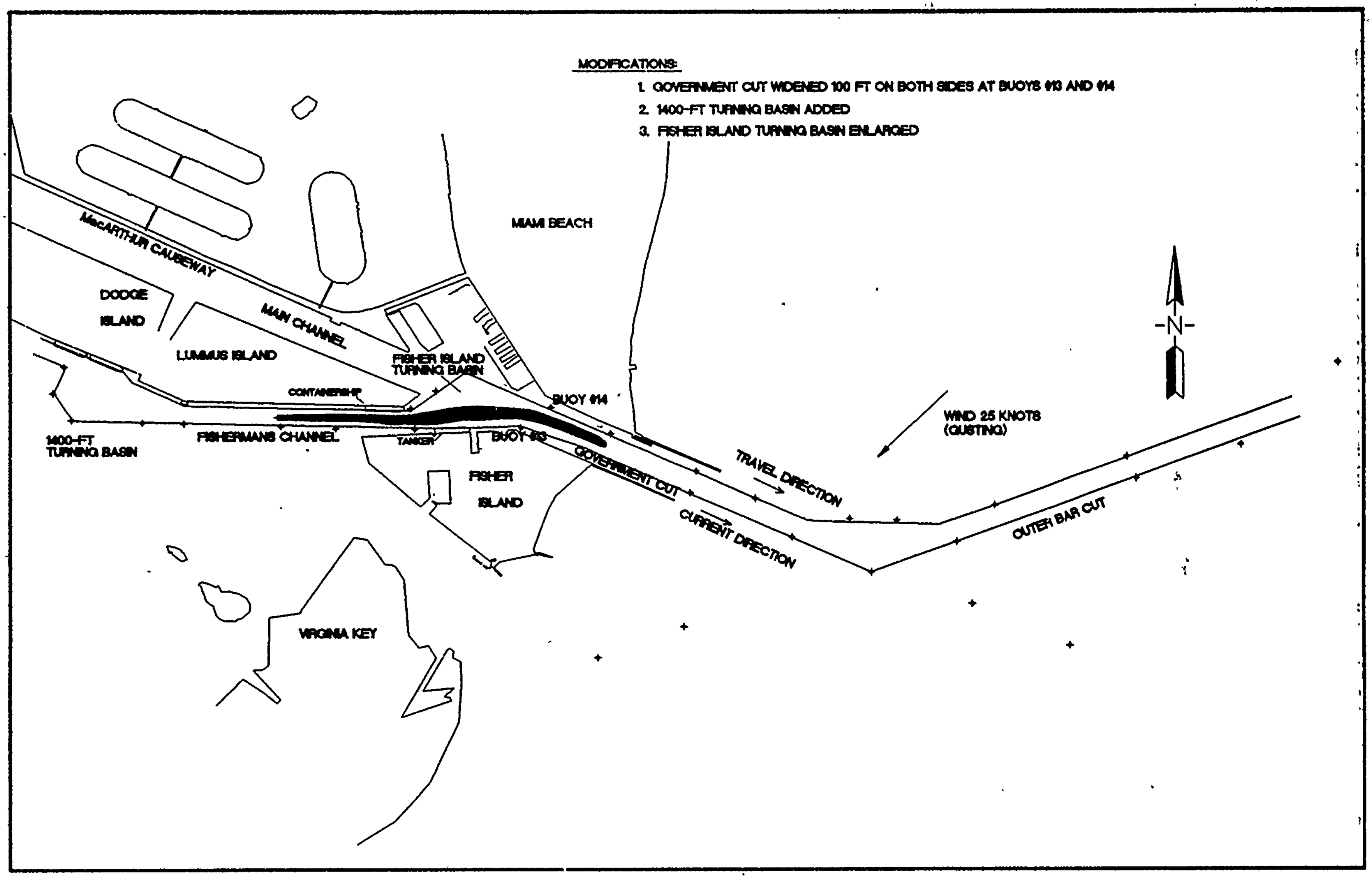


Figure 76. Composite track plots, alternative channel, 950-ft containership, 38-ft draft, ebb tide, 25-knot northeast wind, outbound, all runs

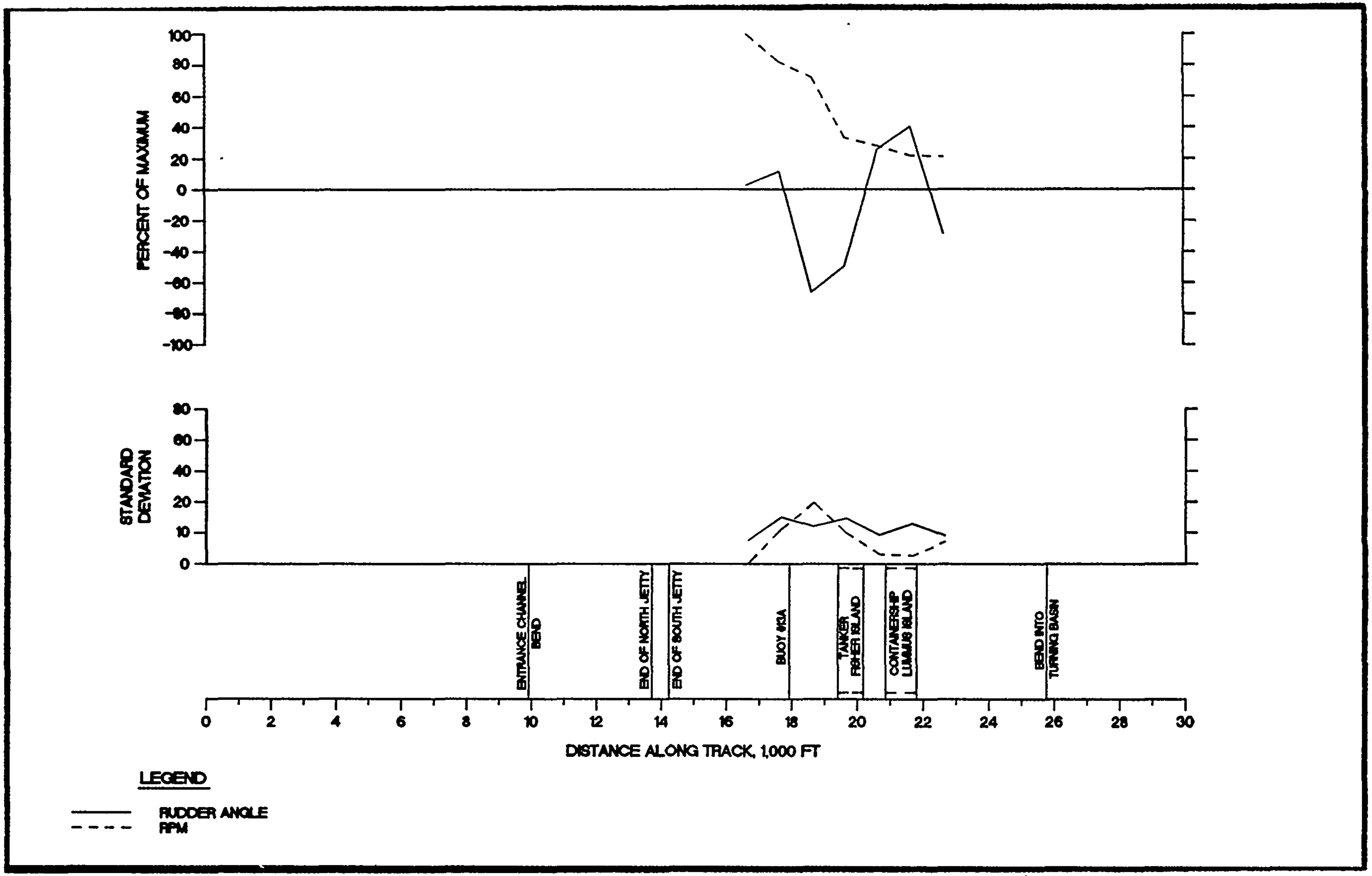


Figure 77. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, outbound, all runs

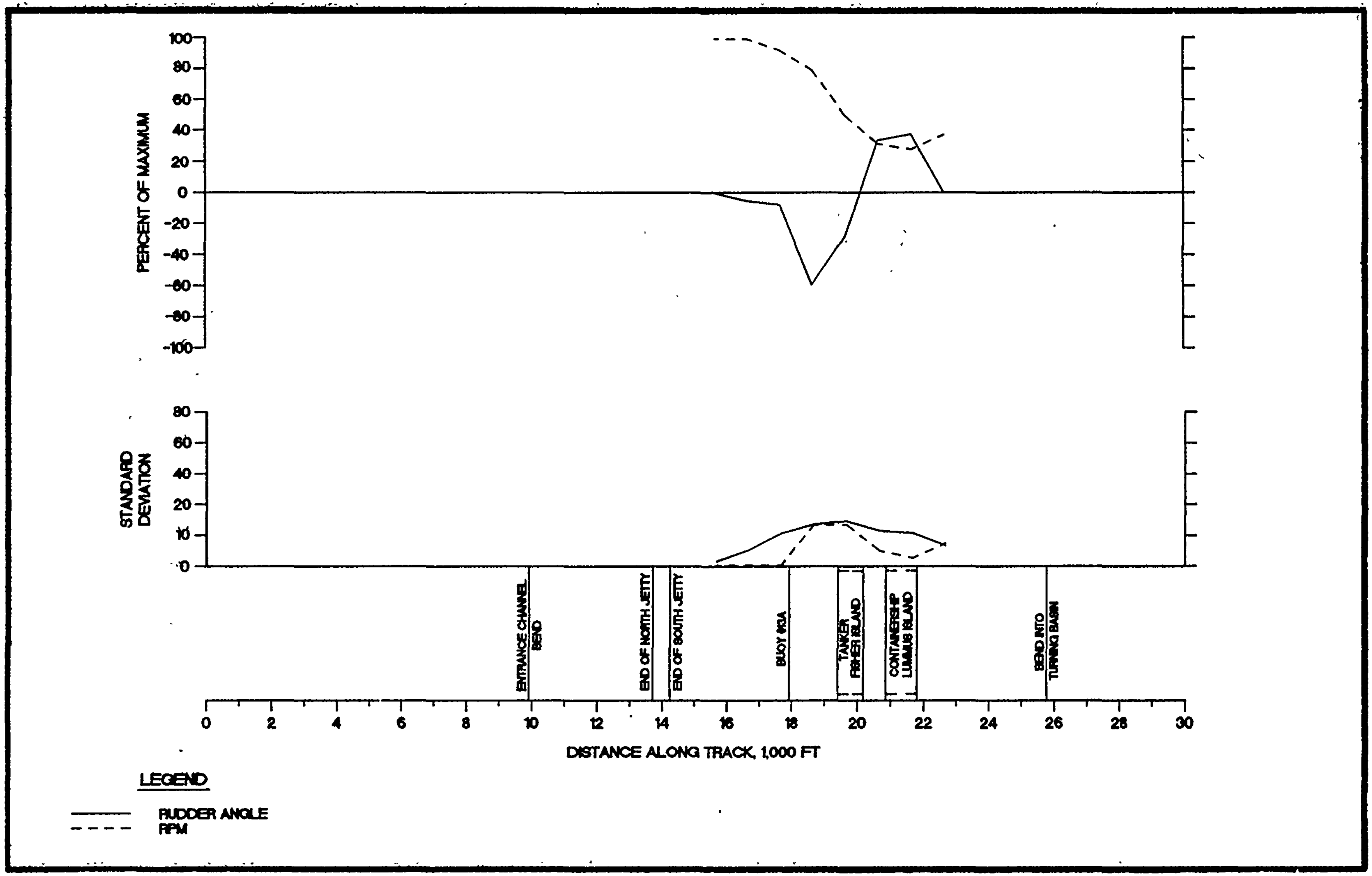


Figure 78. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

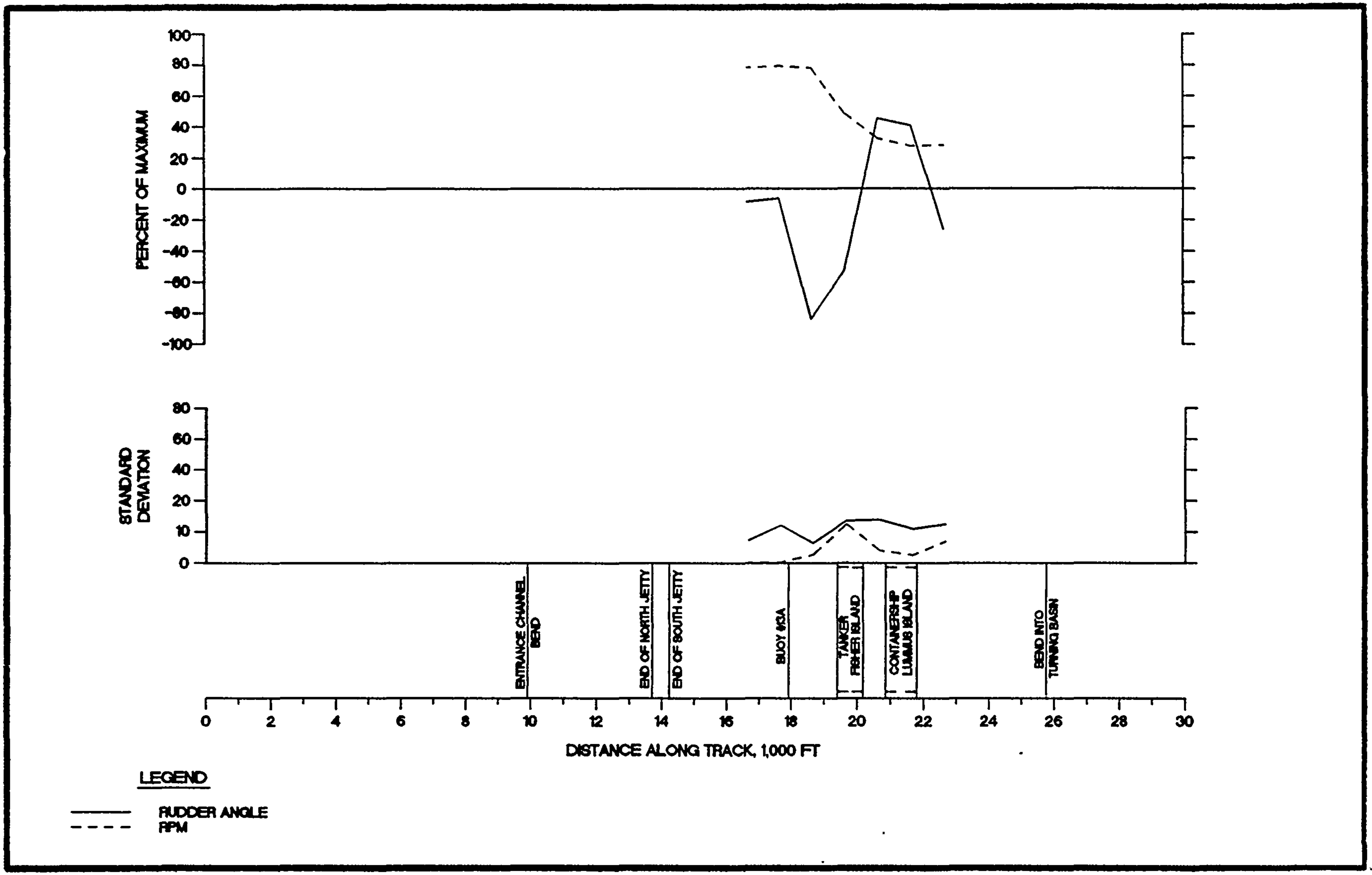


Figure 79. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, outbound, all runs

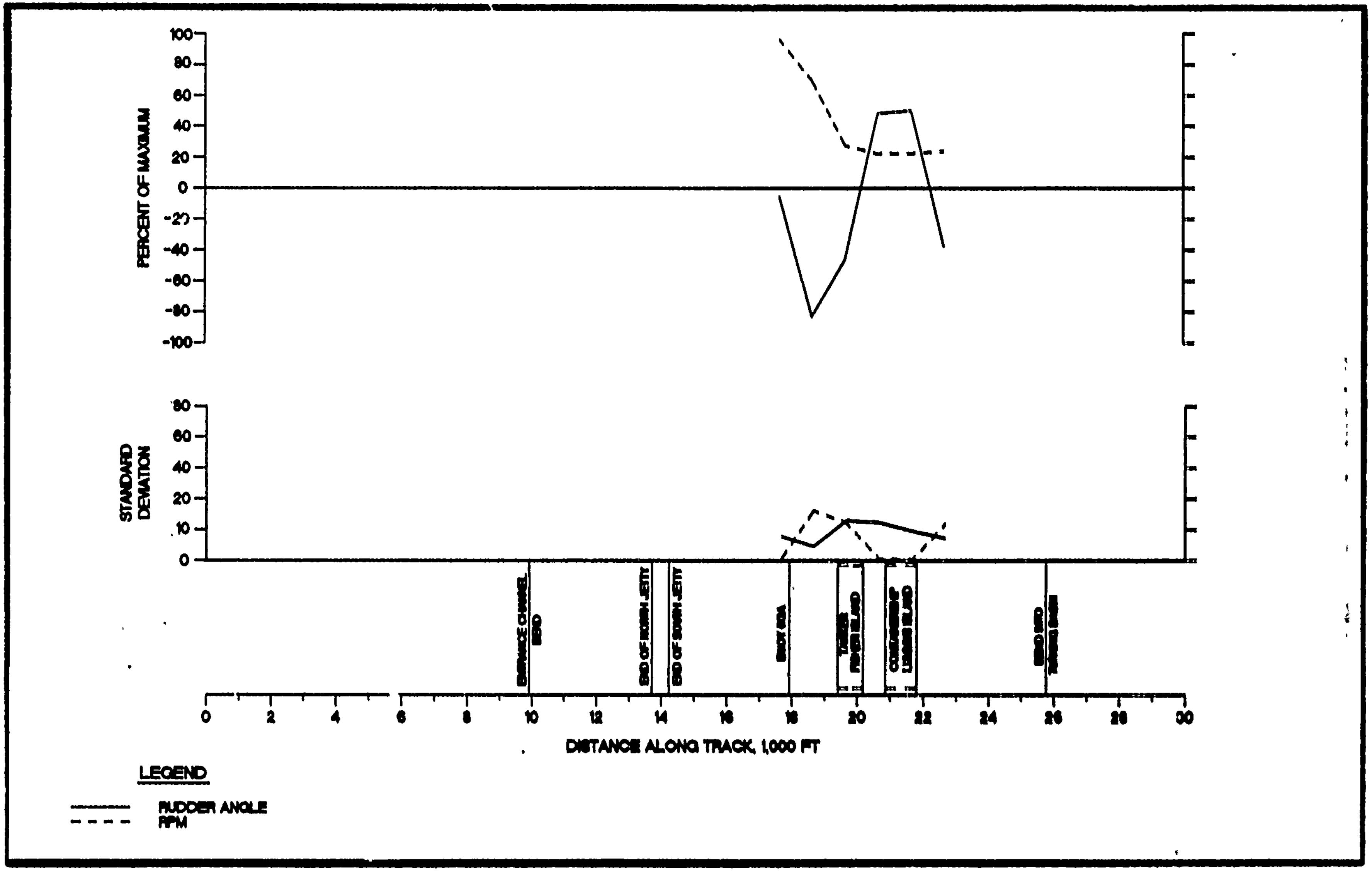


Figure 80. Rudder angle and rpm, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, outbound, all runs

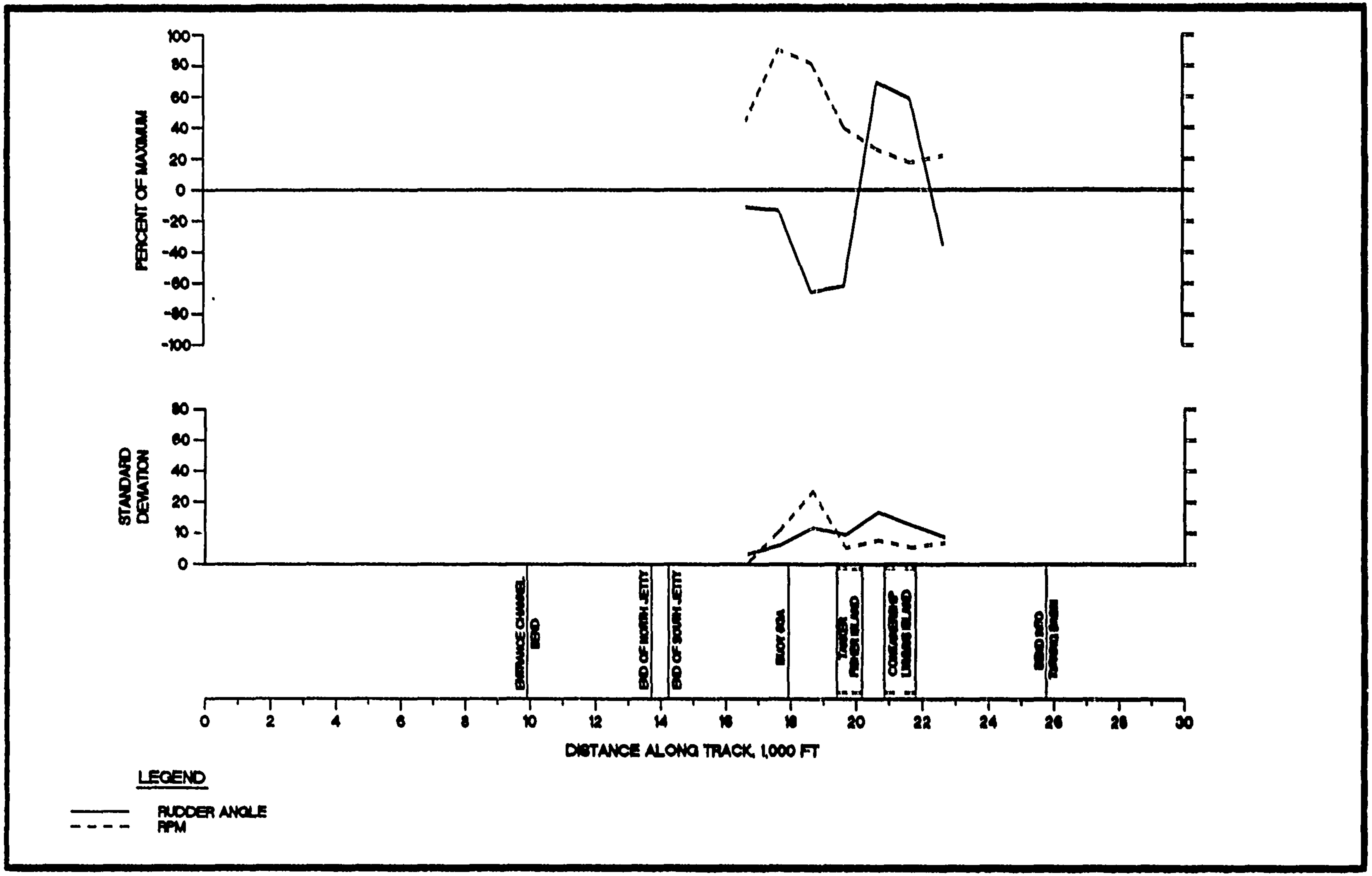


Figure 81. Rudder angle and rpm, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, outbound, all runs

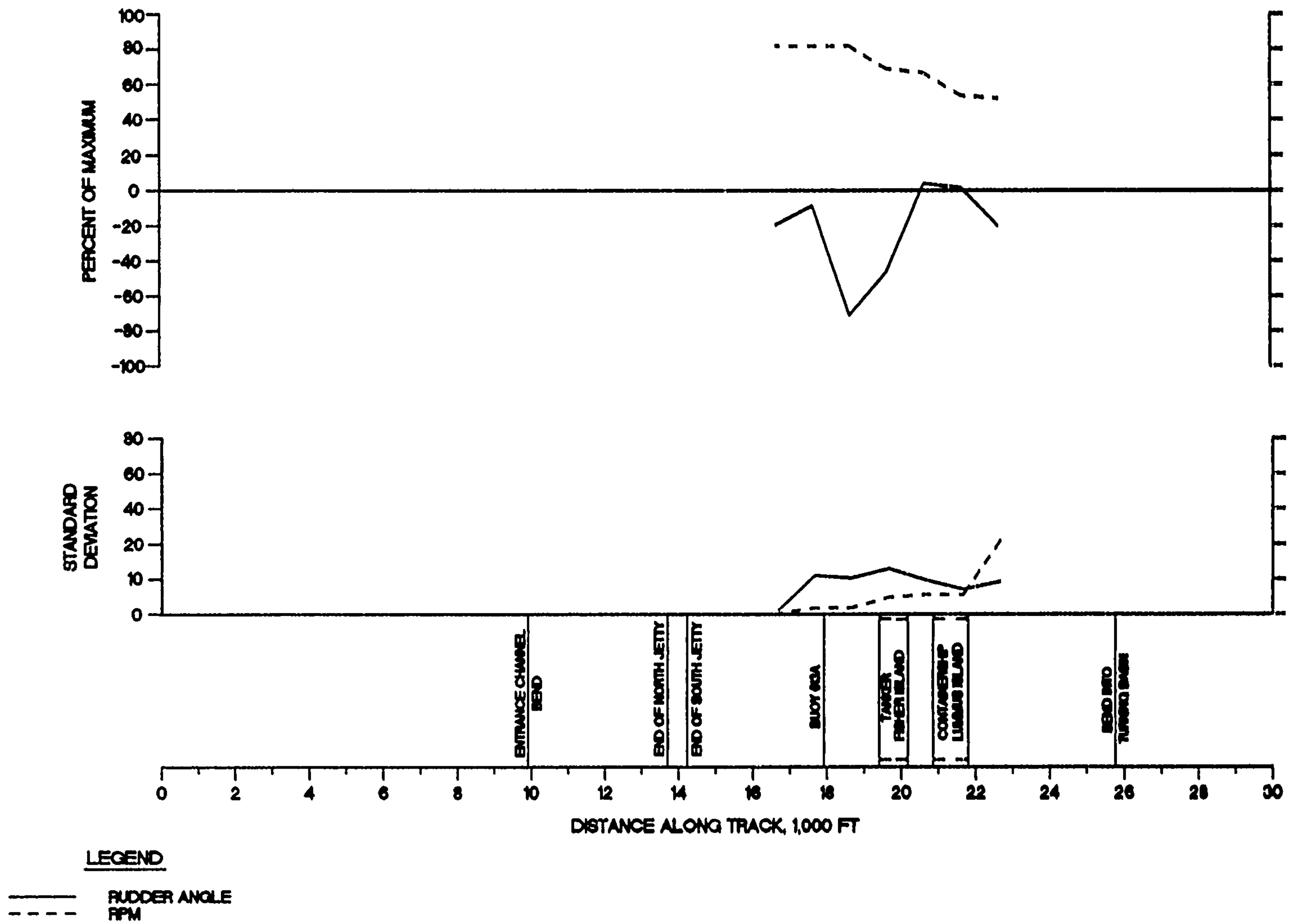


Figure 82. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, outbound, all runs

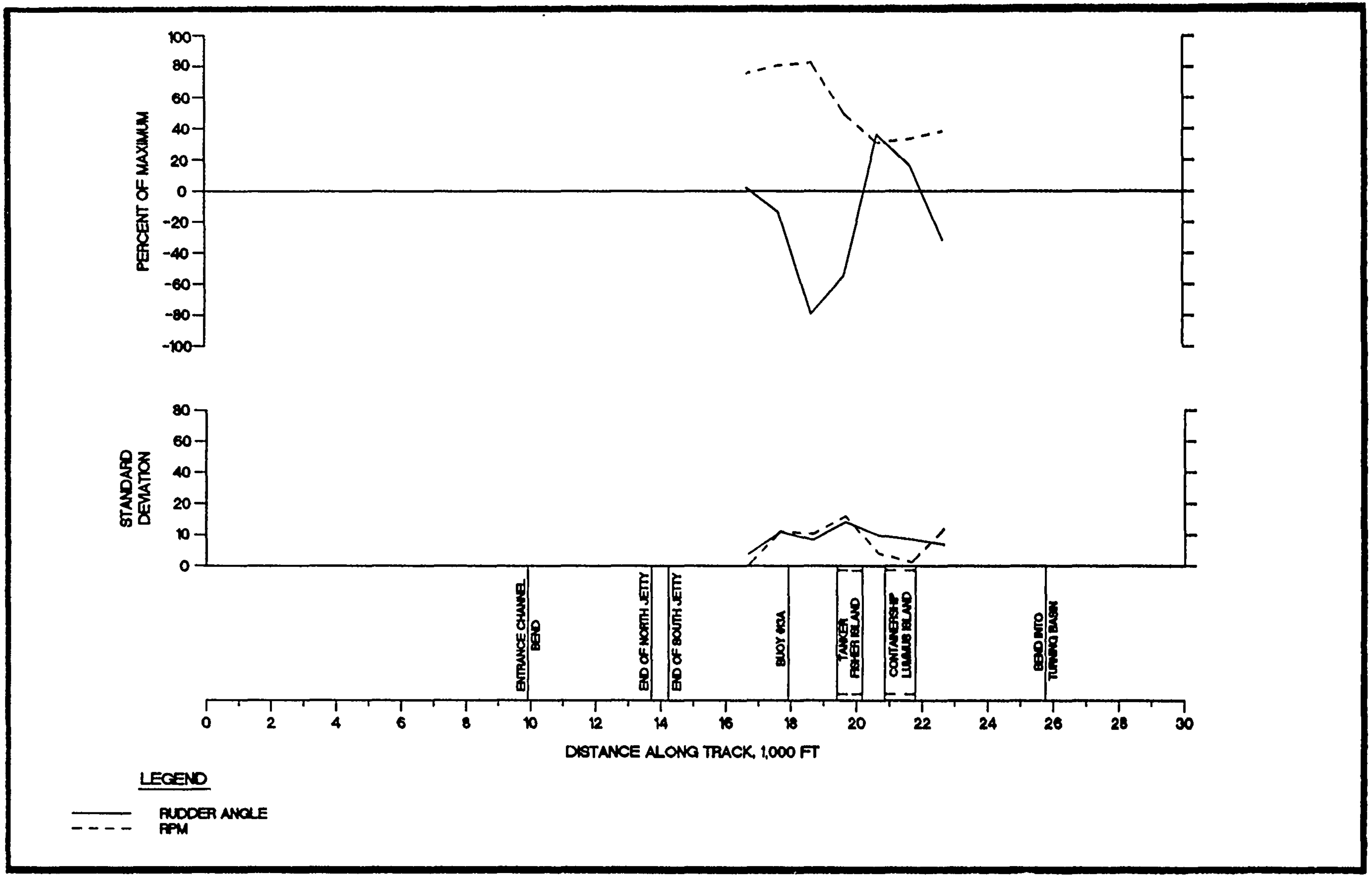


Figure 83. Rudder angle and rpm, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

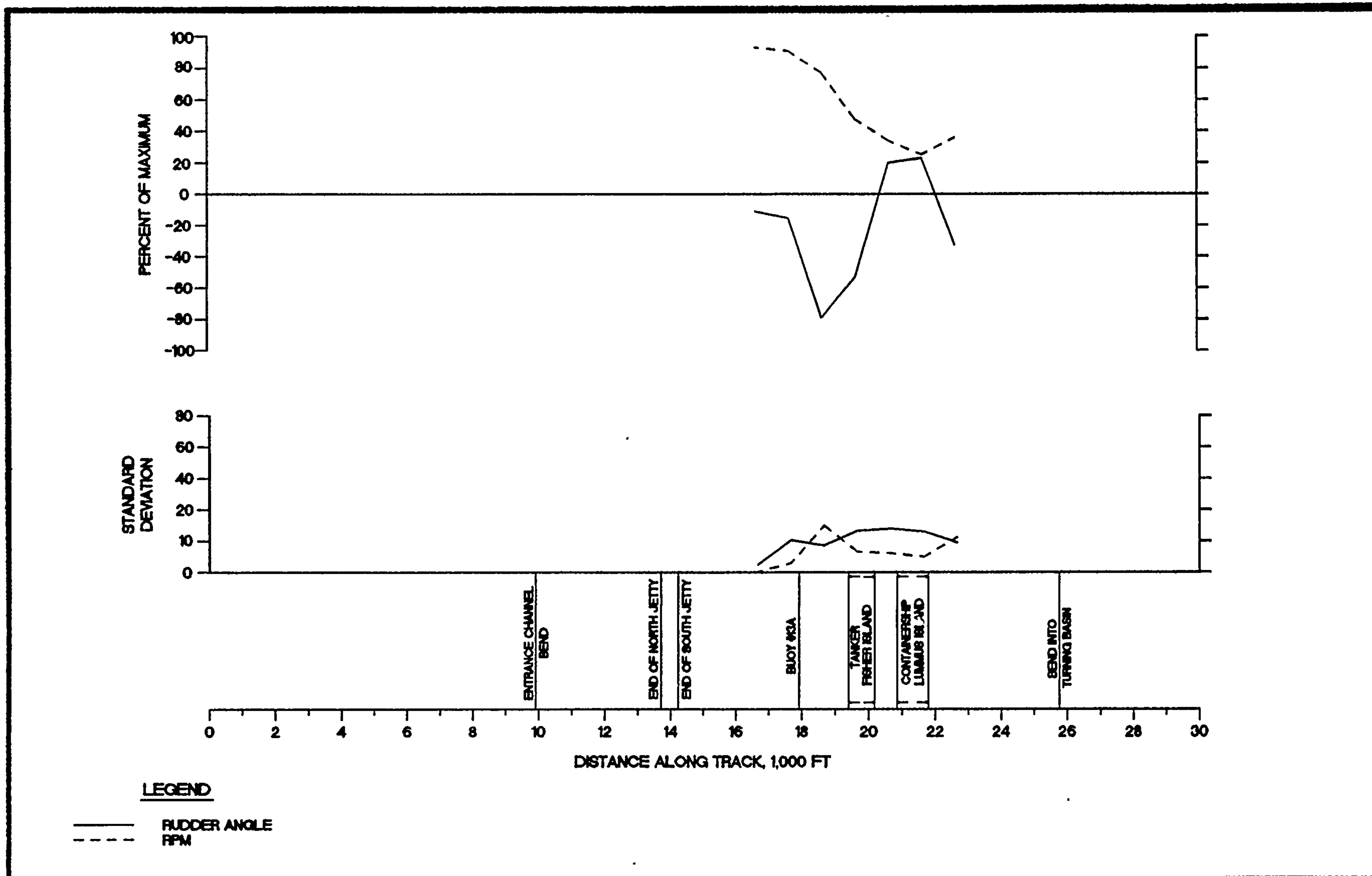


Figure 84. Rudder angle and rpm, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

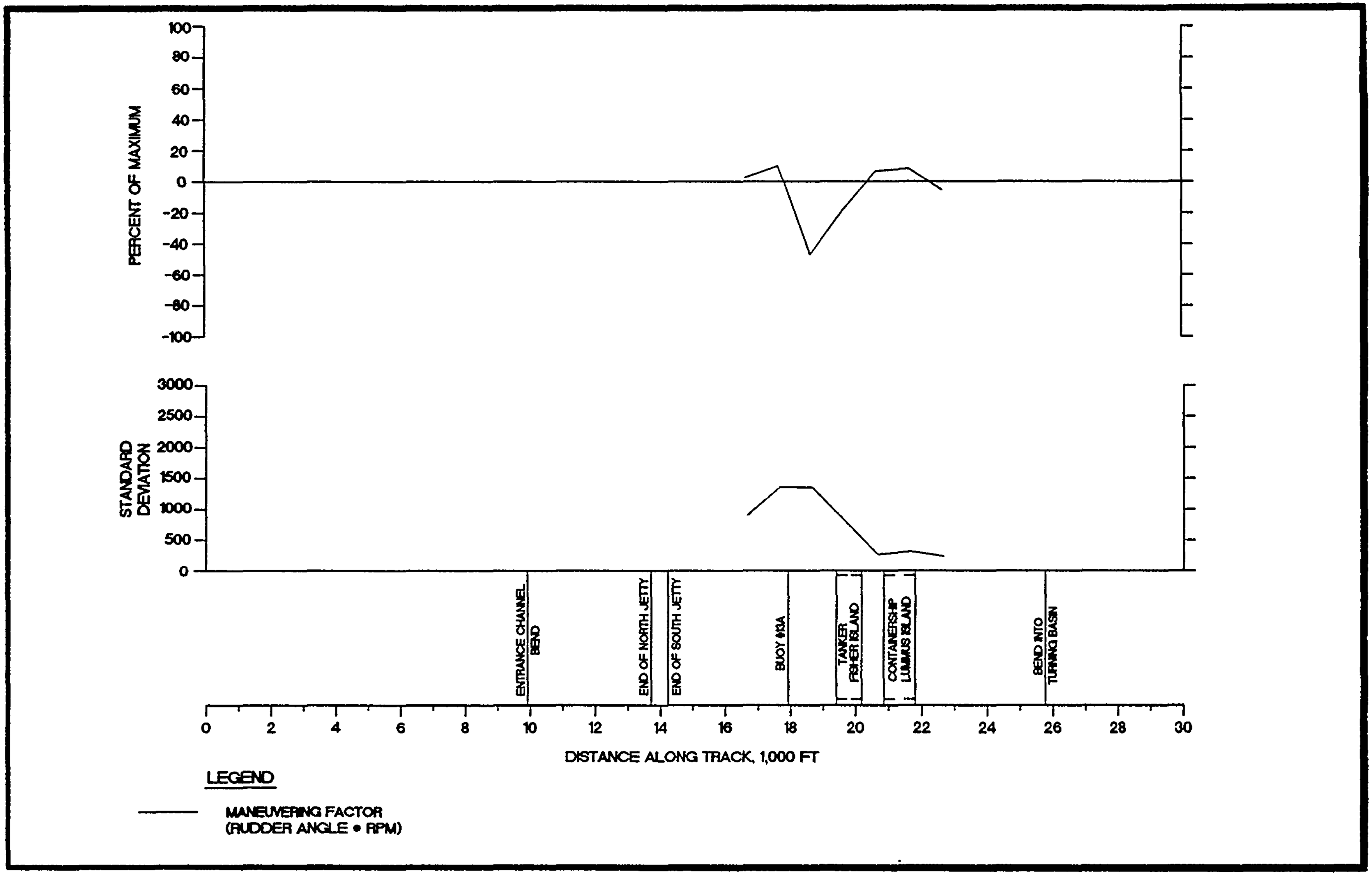


Figure 85. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, outbound, all runs

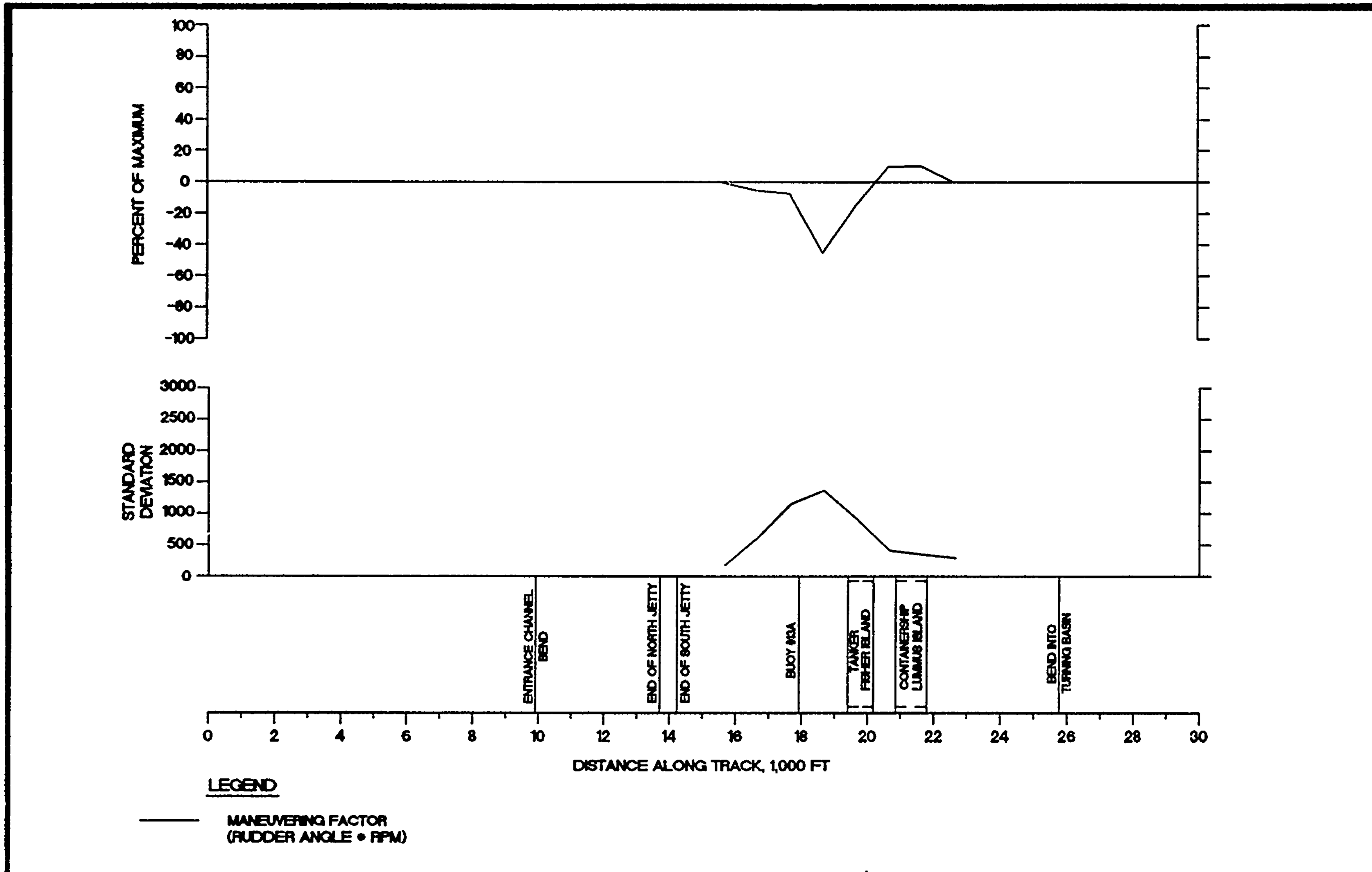


Figure 86. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

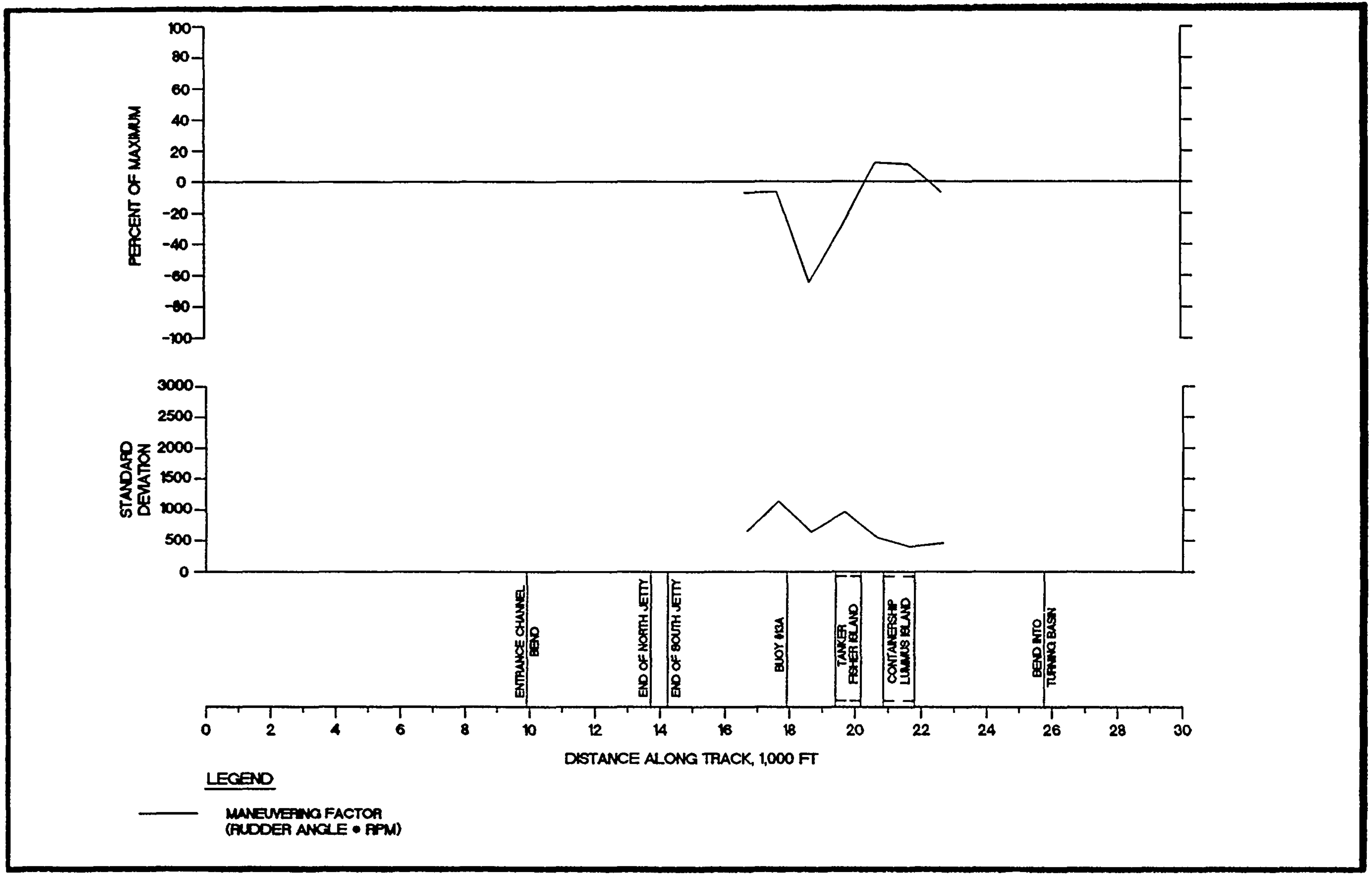


Figure 87. Maneuvering factor, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, outbound, all runs

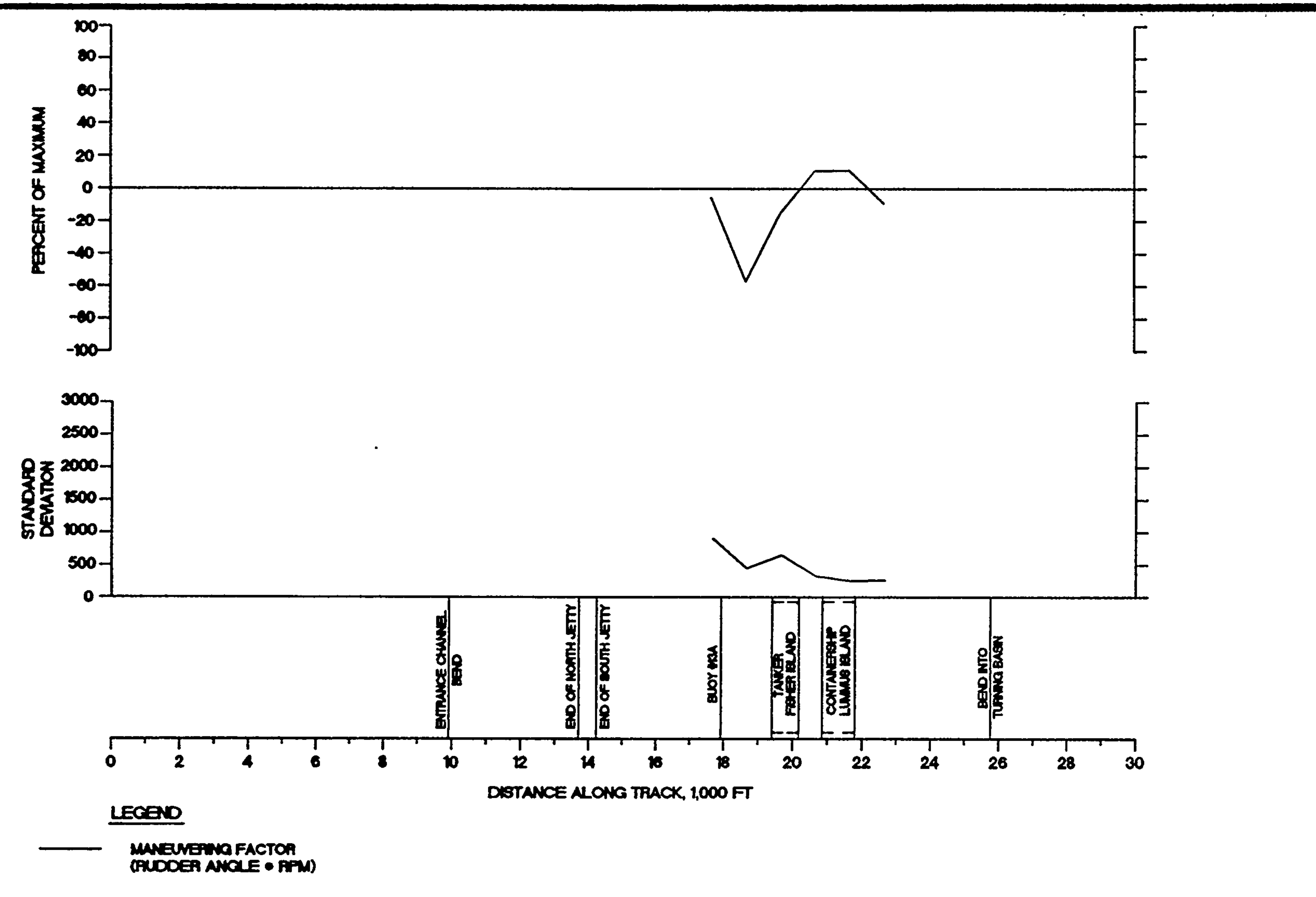


Figure 88. Maneuvering factor, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, outbound, all runs

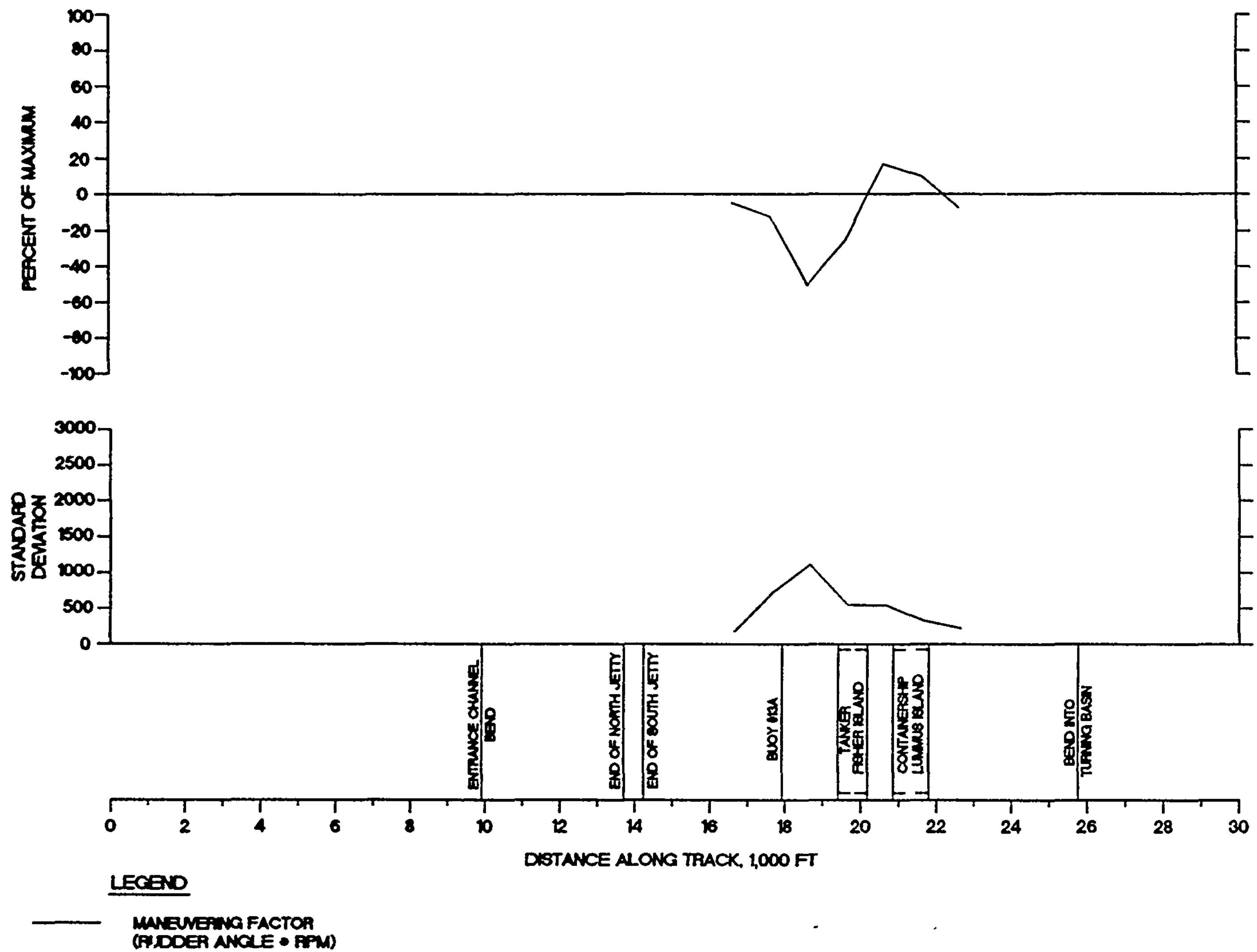


Figure 89. Maneuvering factor, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, outbound, all runs

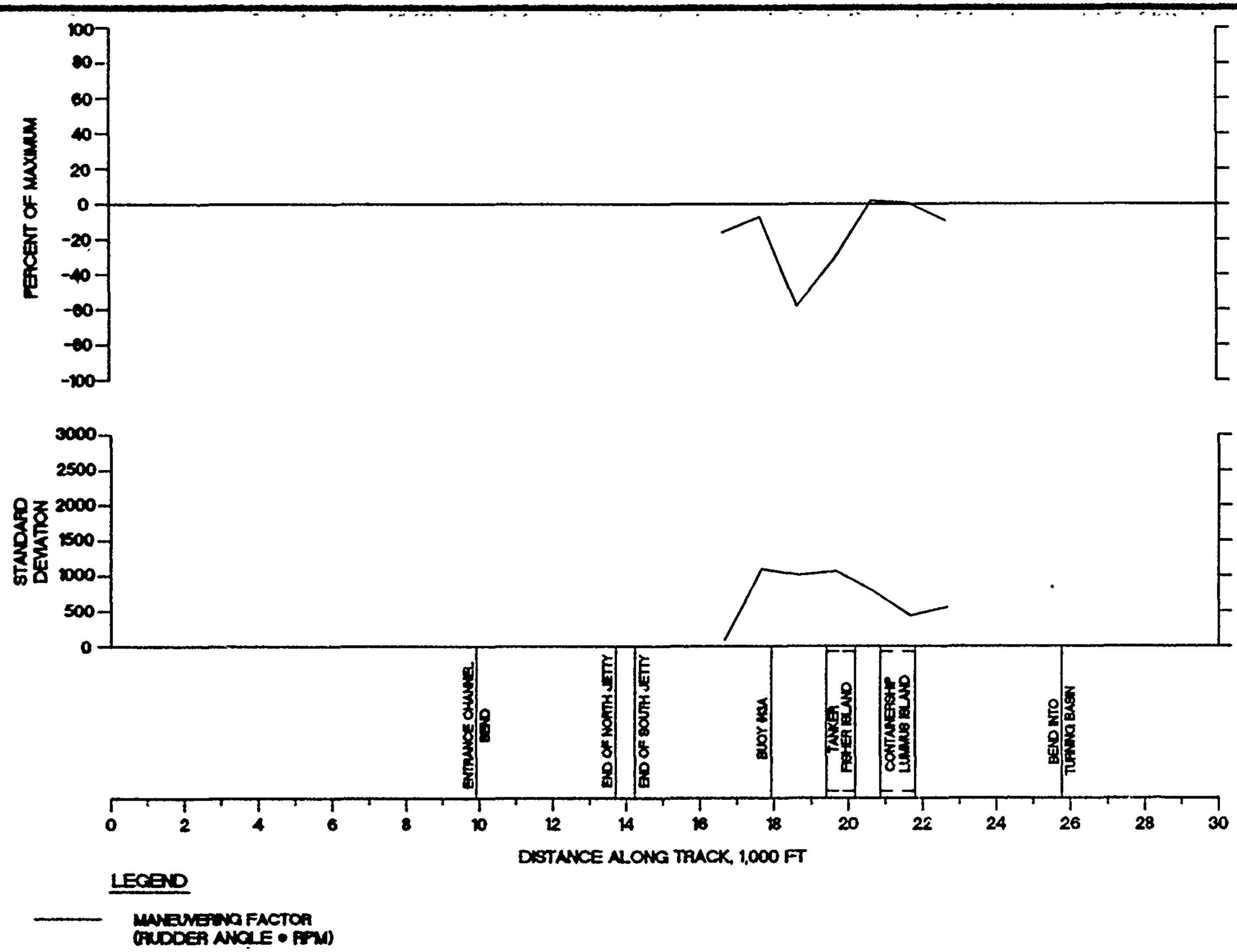


Figure 90. Maneuvering factor, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, outbound, all runs

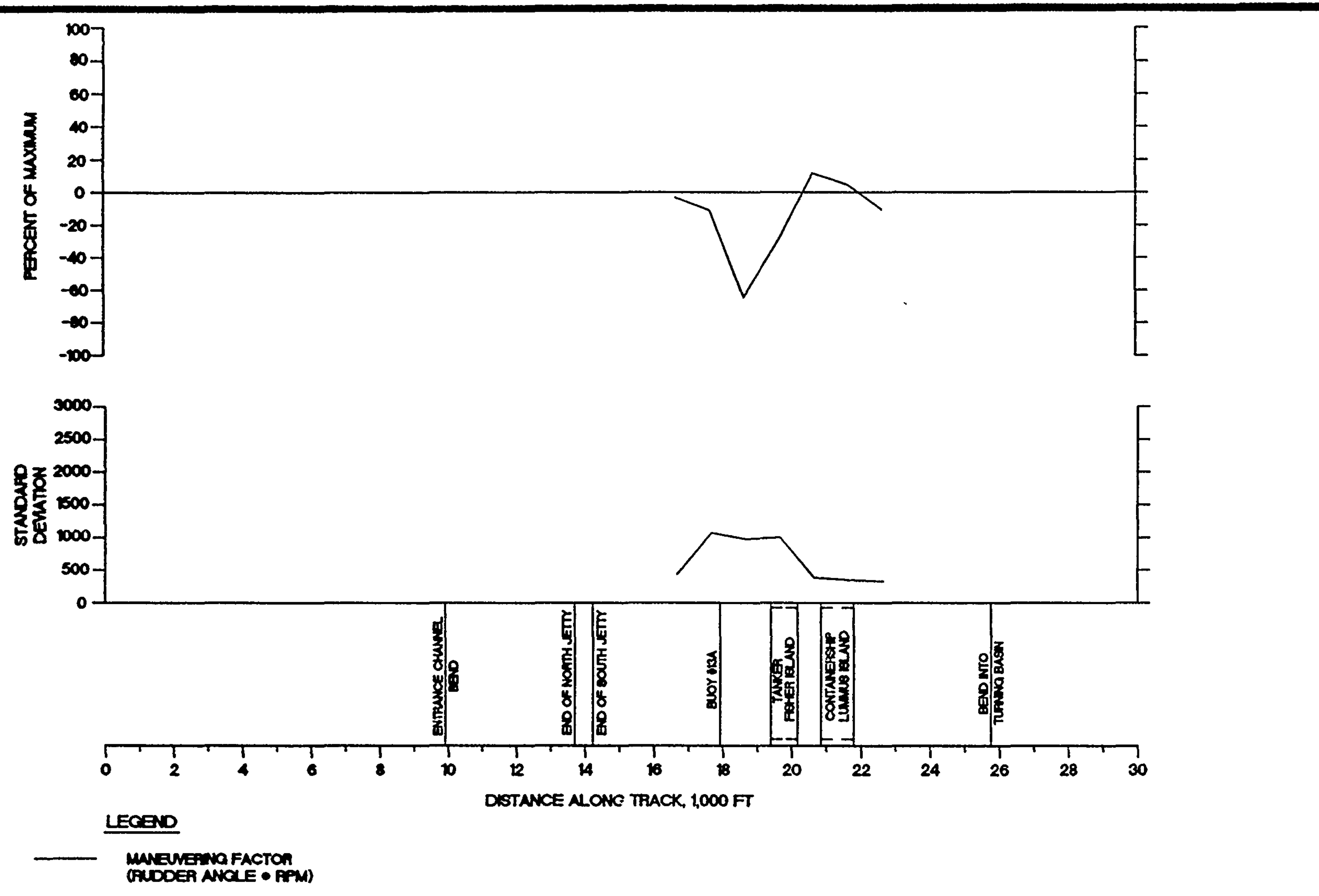


Figure 91. Maneuvering factor, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

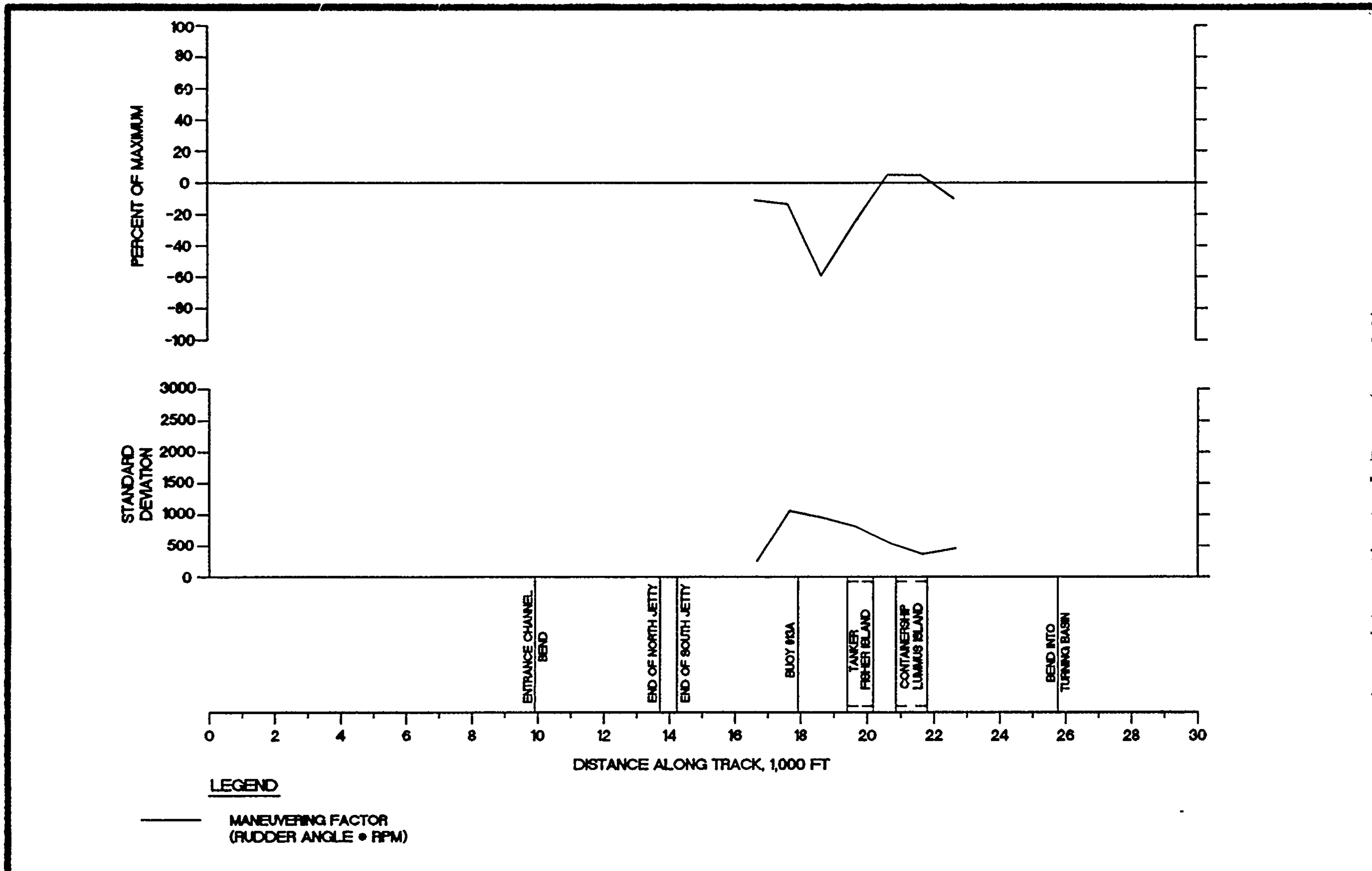


Figure 92. Maneuvering factor, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

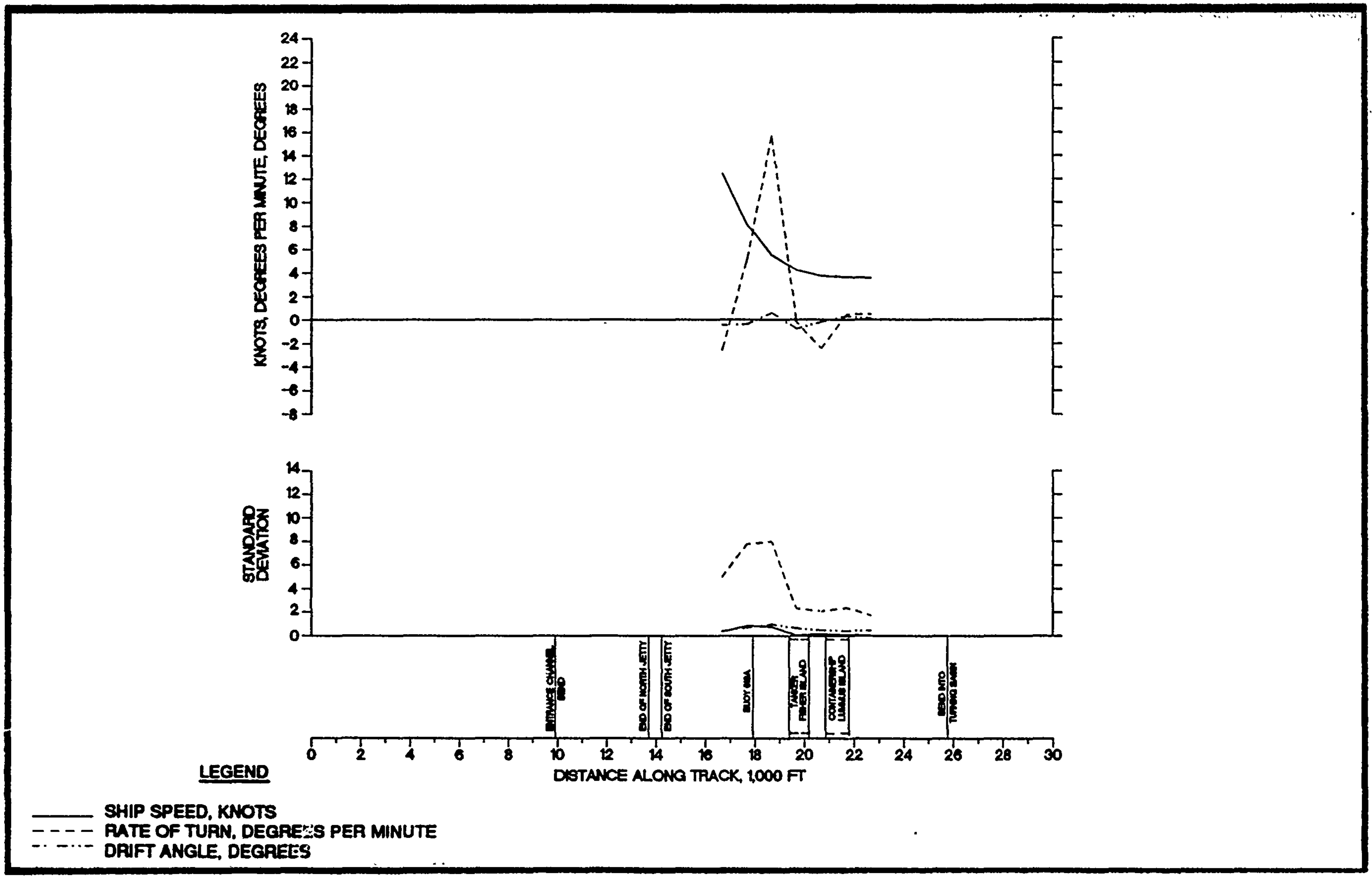


Figure 93. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, outbound, all runs

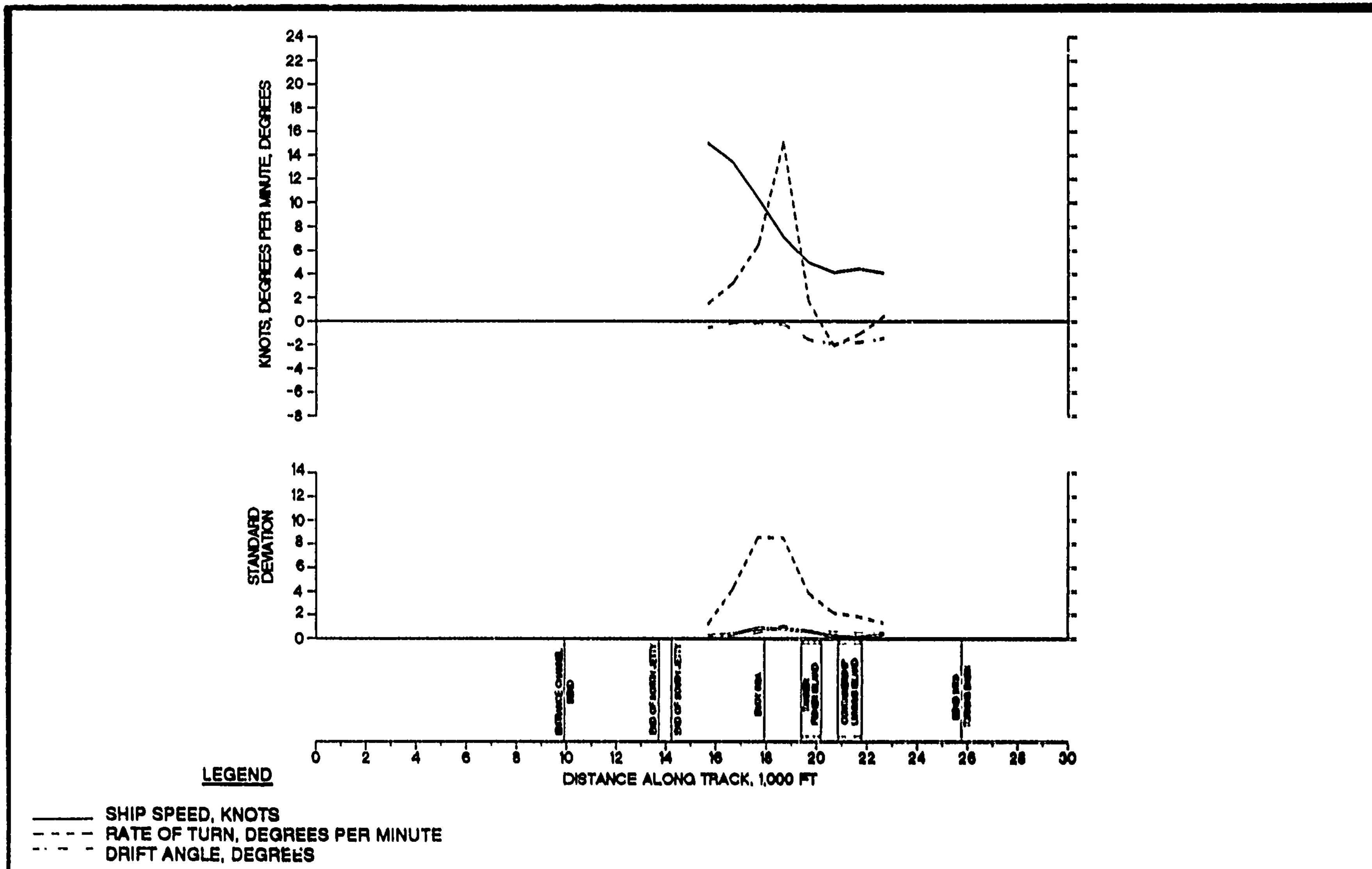


Figure 94. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

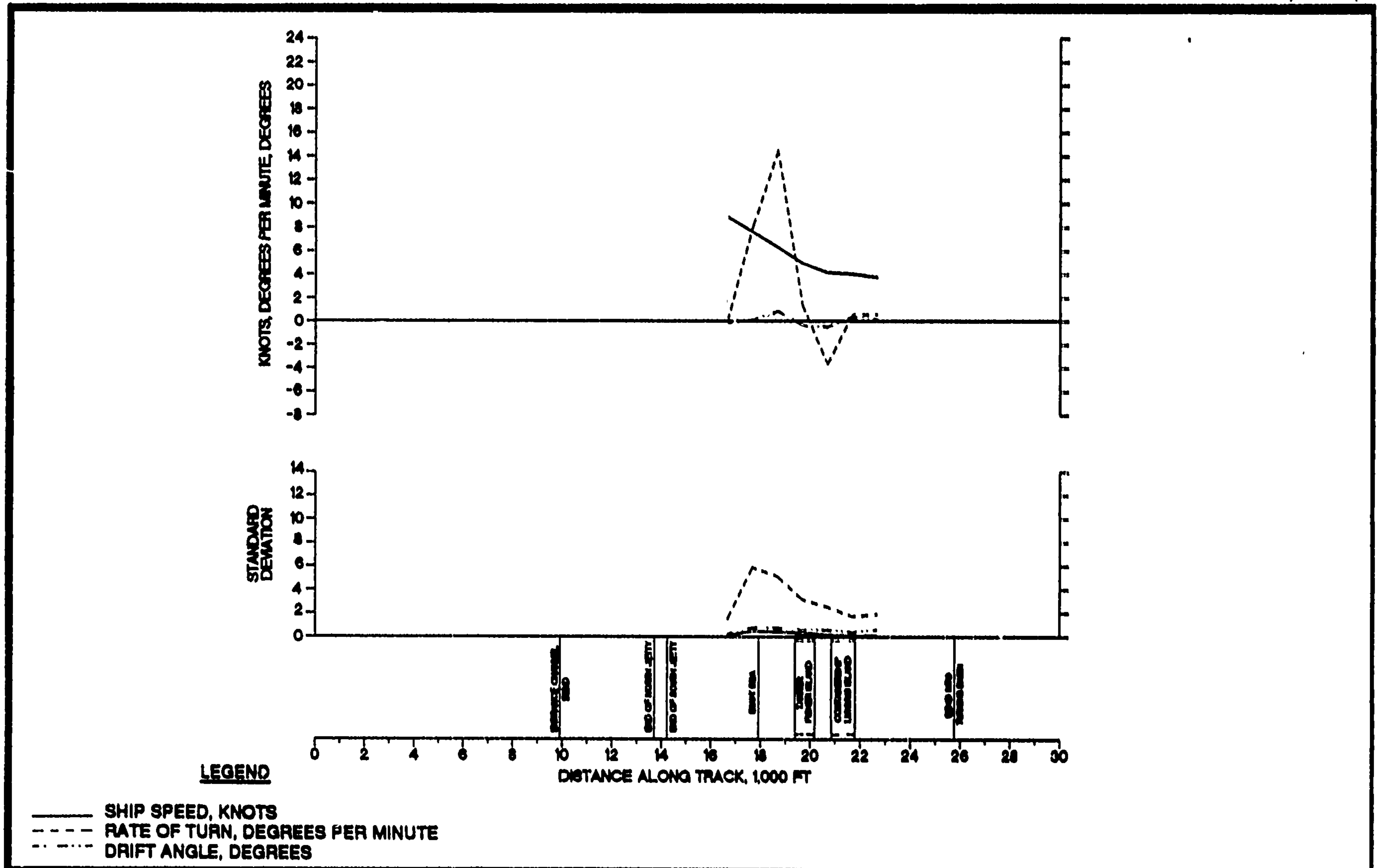


Figure 95. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, outbound, all runs

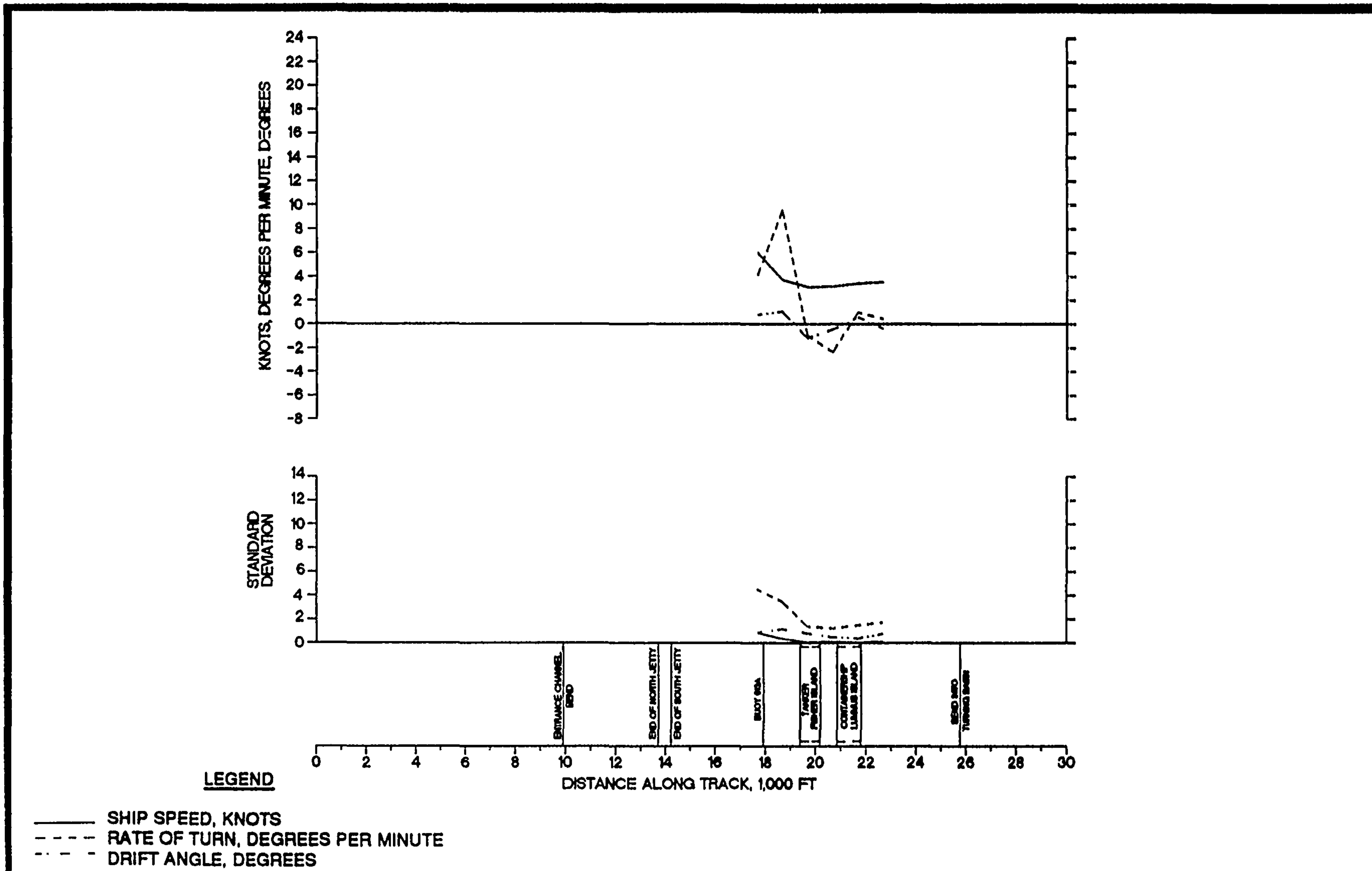


Figure 96. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, outbound, all runs

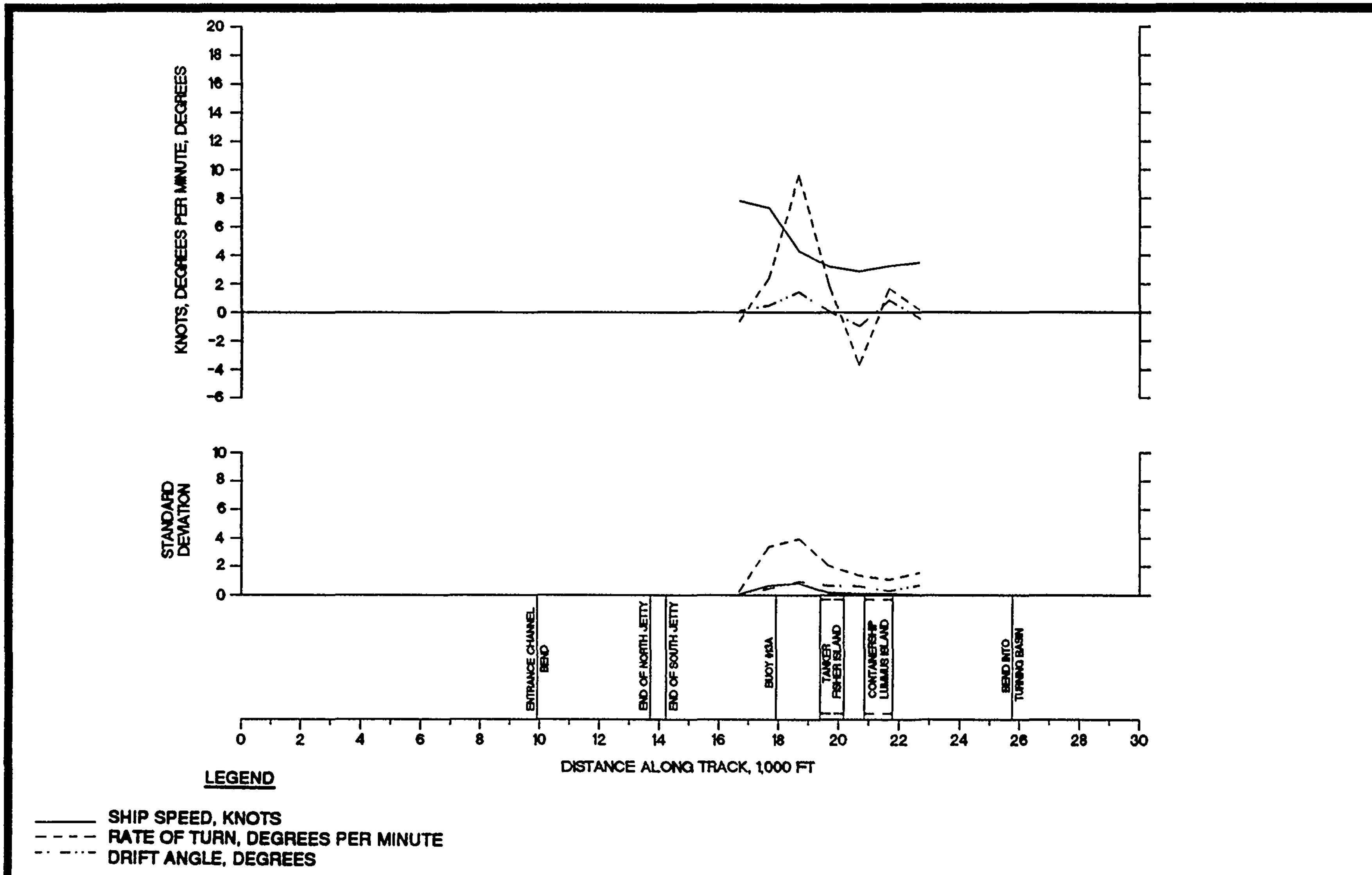


Figure 97. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, outbound, all runs

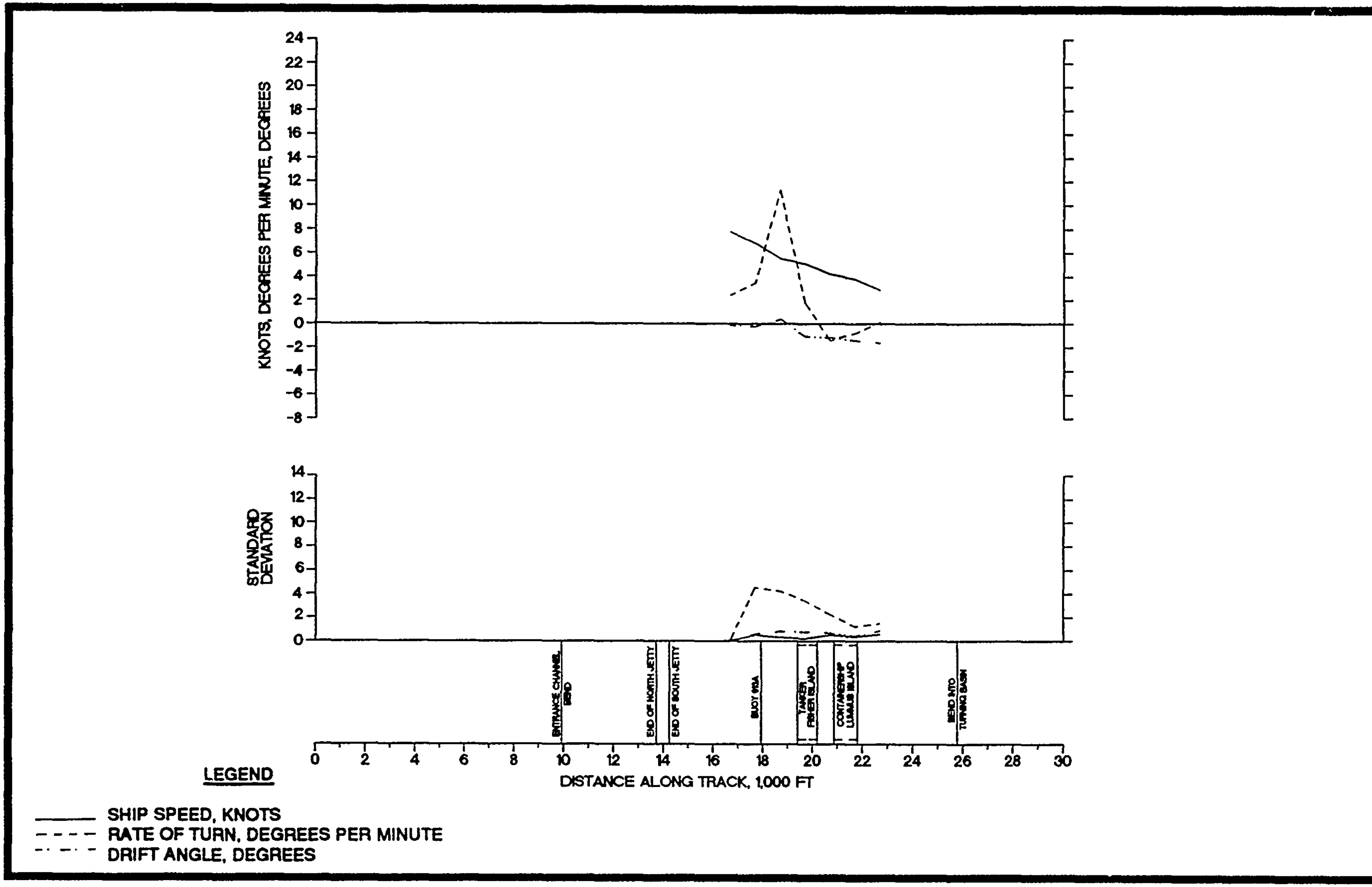


Figure 98. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, outbound, all runs

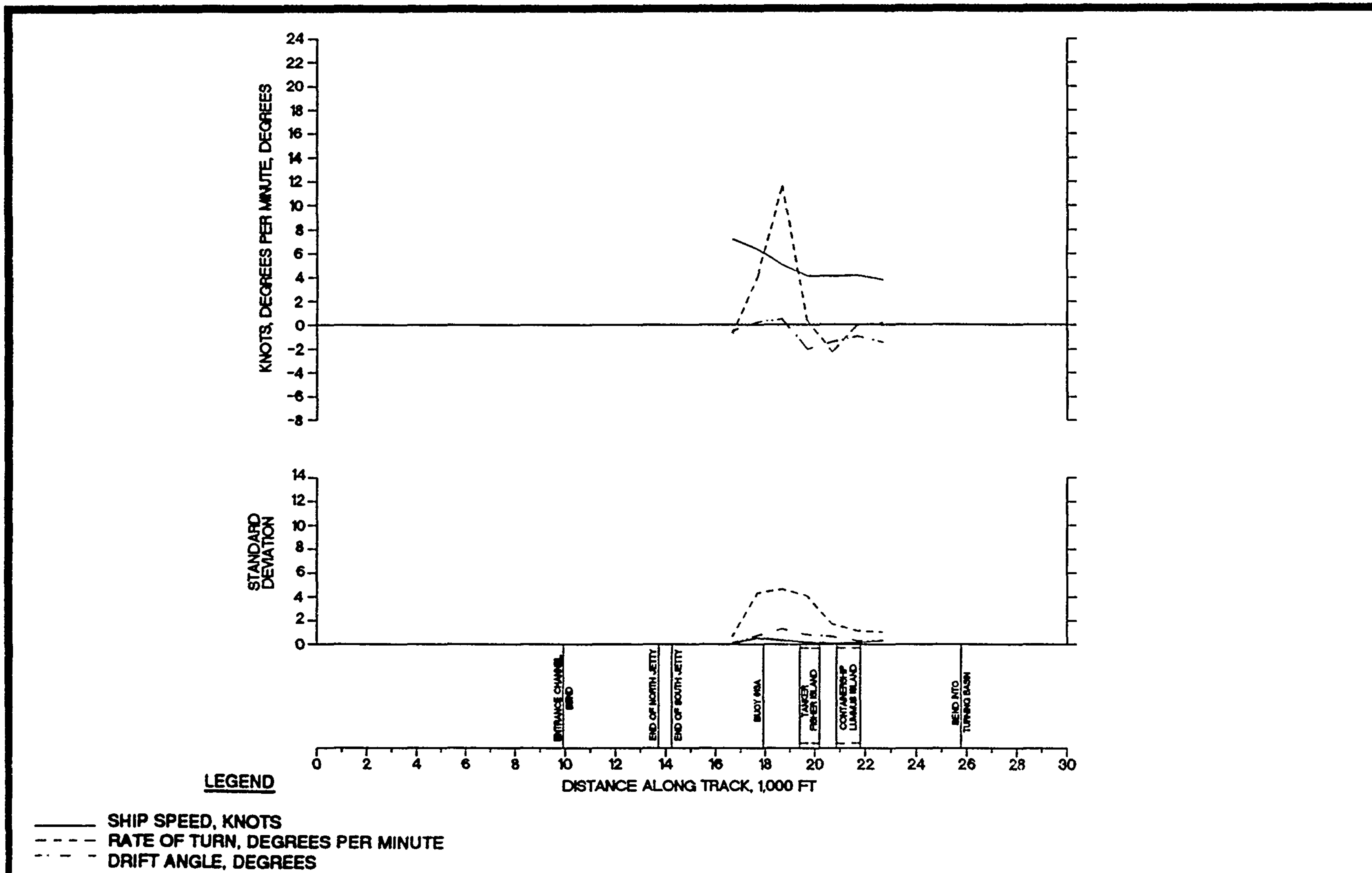


Figure 99. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

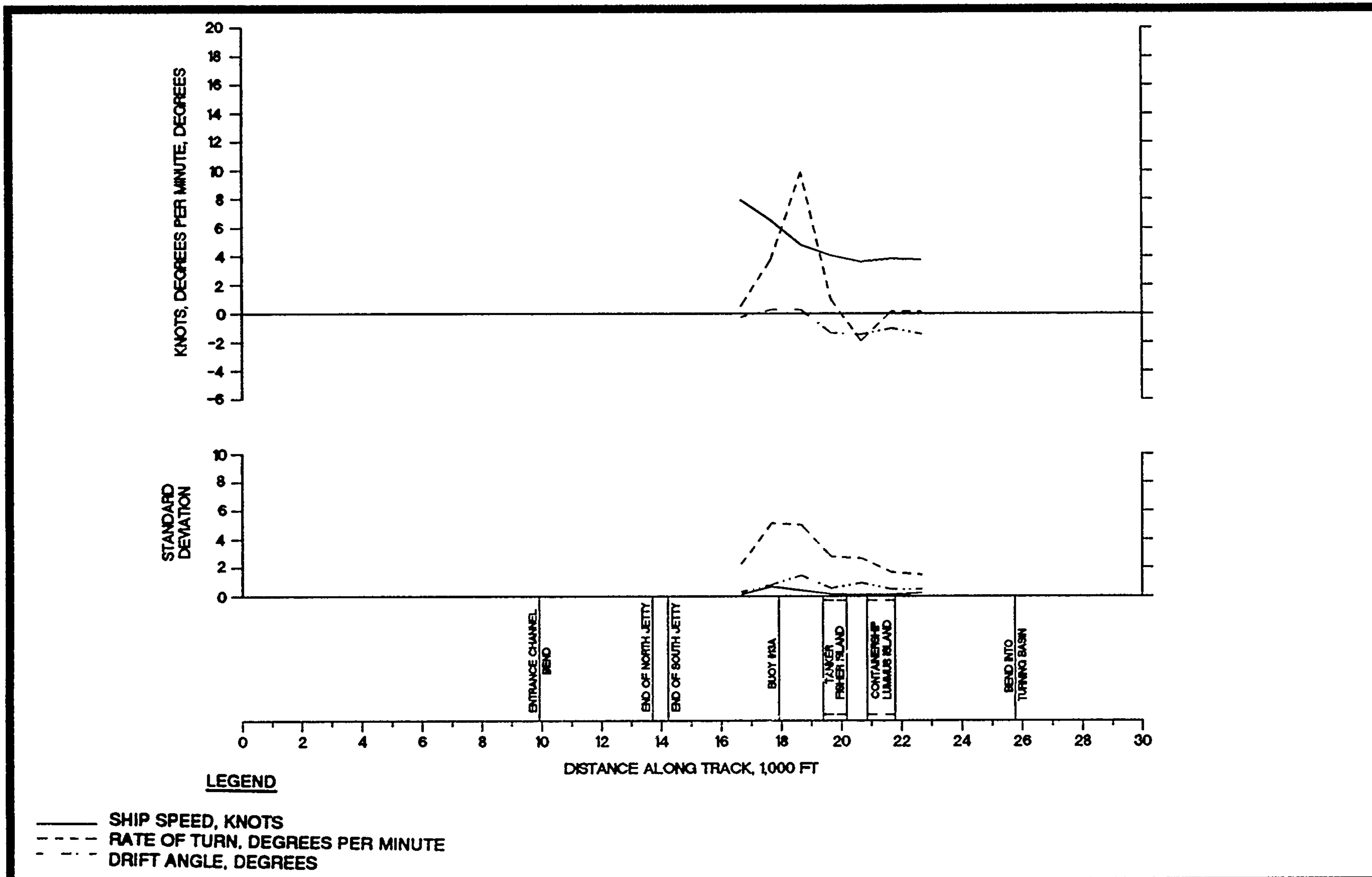


Figure 100. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

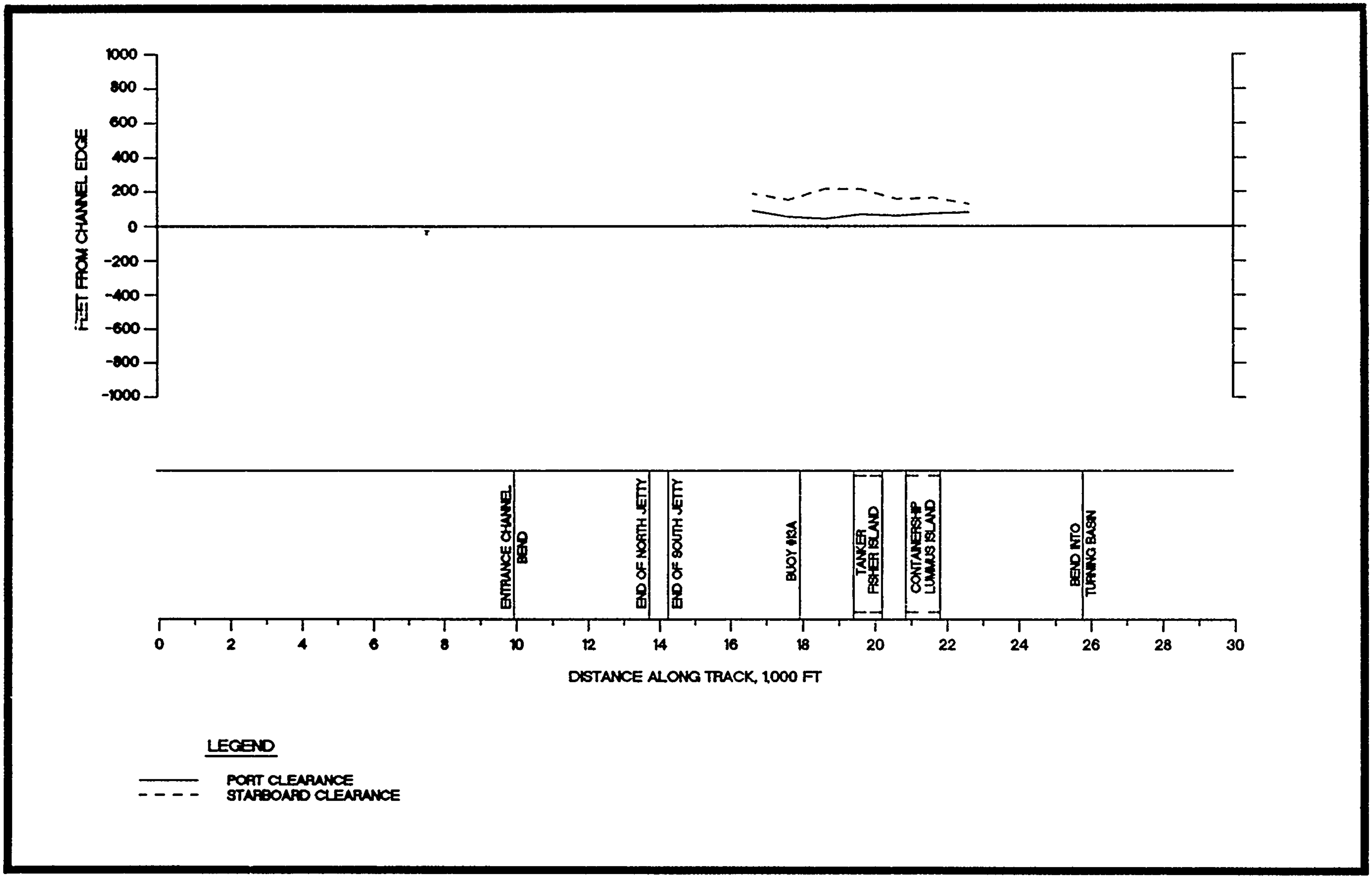


Figure 101. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, outbound, all runs

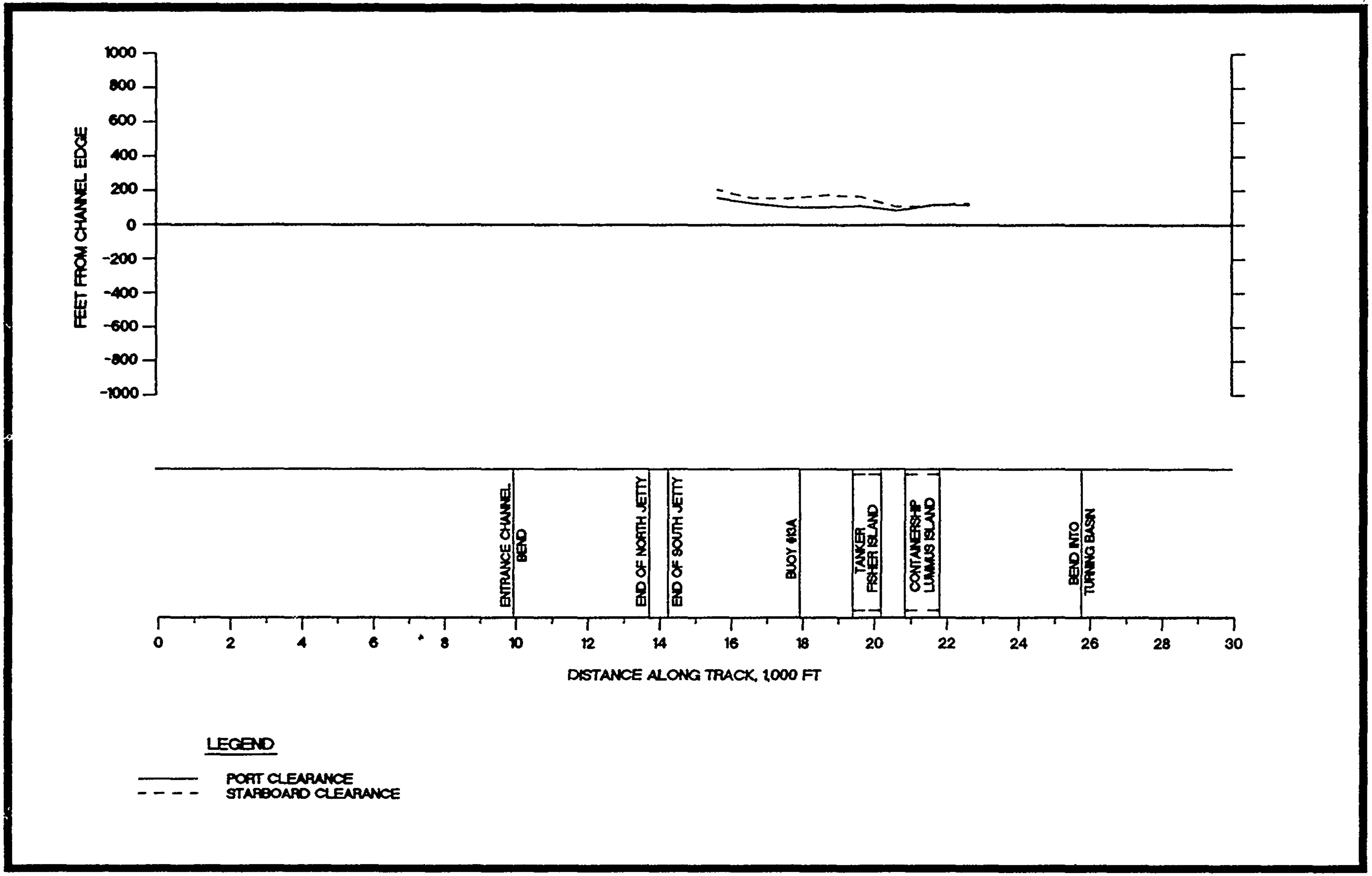


Figure 102. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

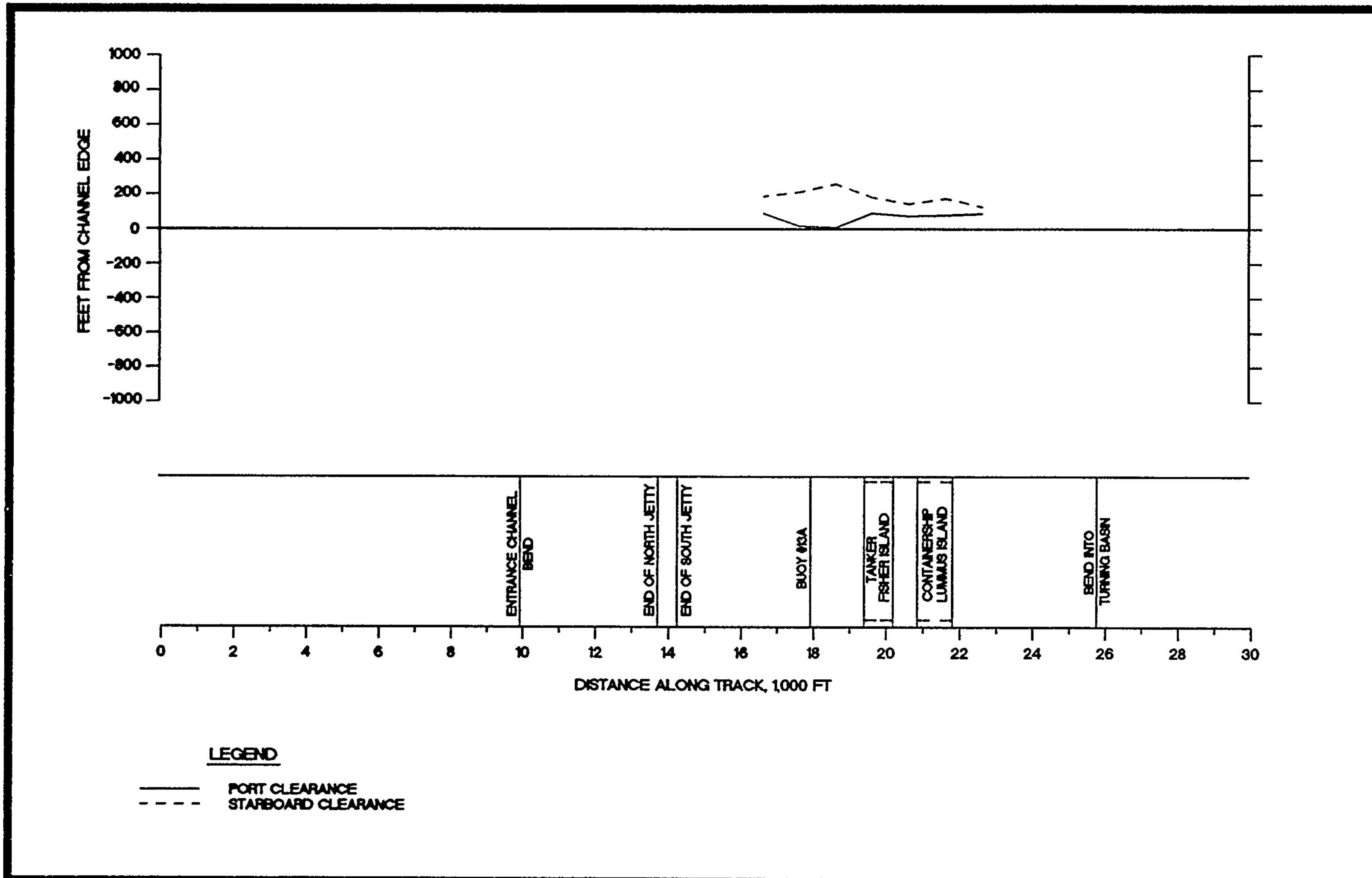


Figure 103. Port and starboard clearance, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, outbound, all runs

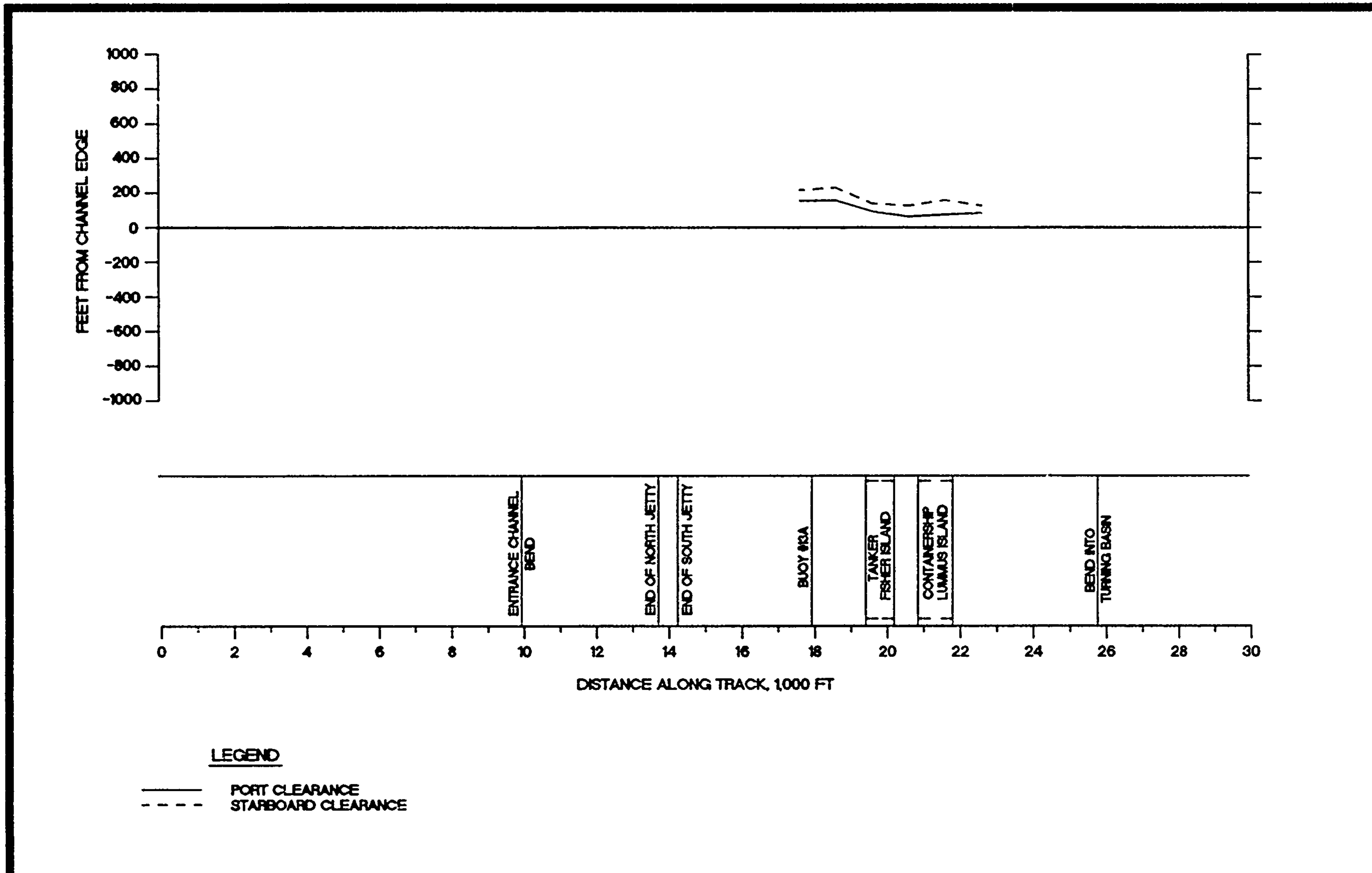


Figure 104. Port and starboard clearance, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, outbound, all runs

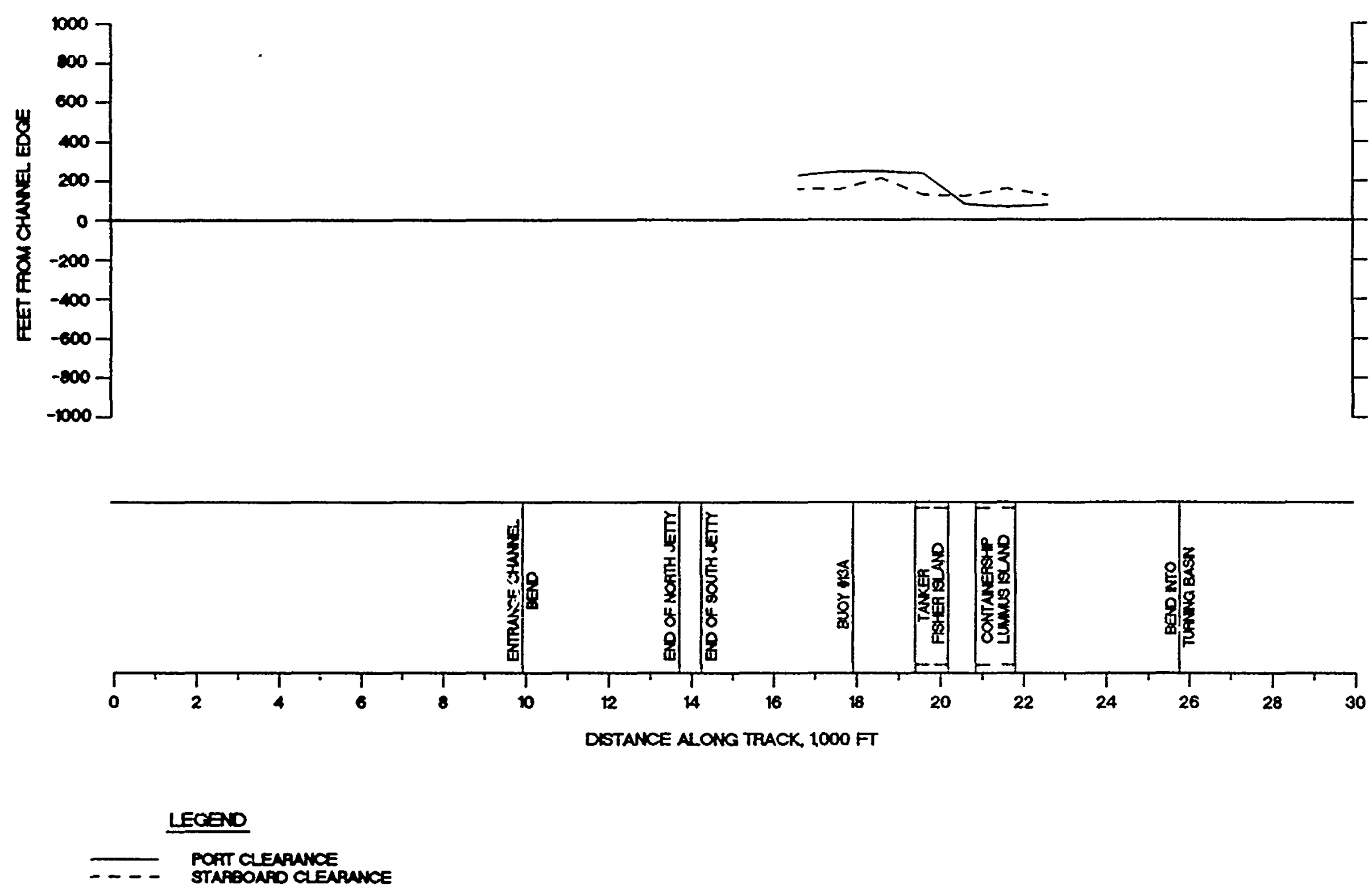


Figure 105. Port and starboard clearance, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, outbound, all runs

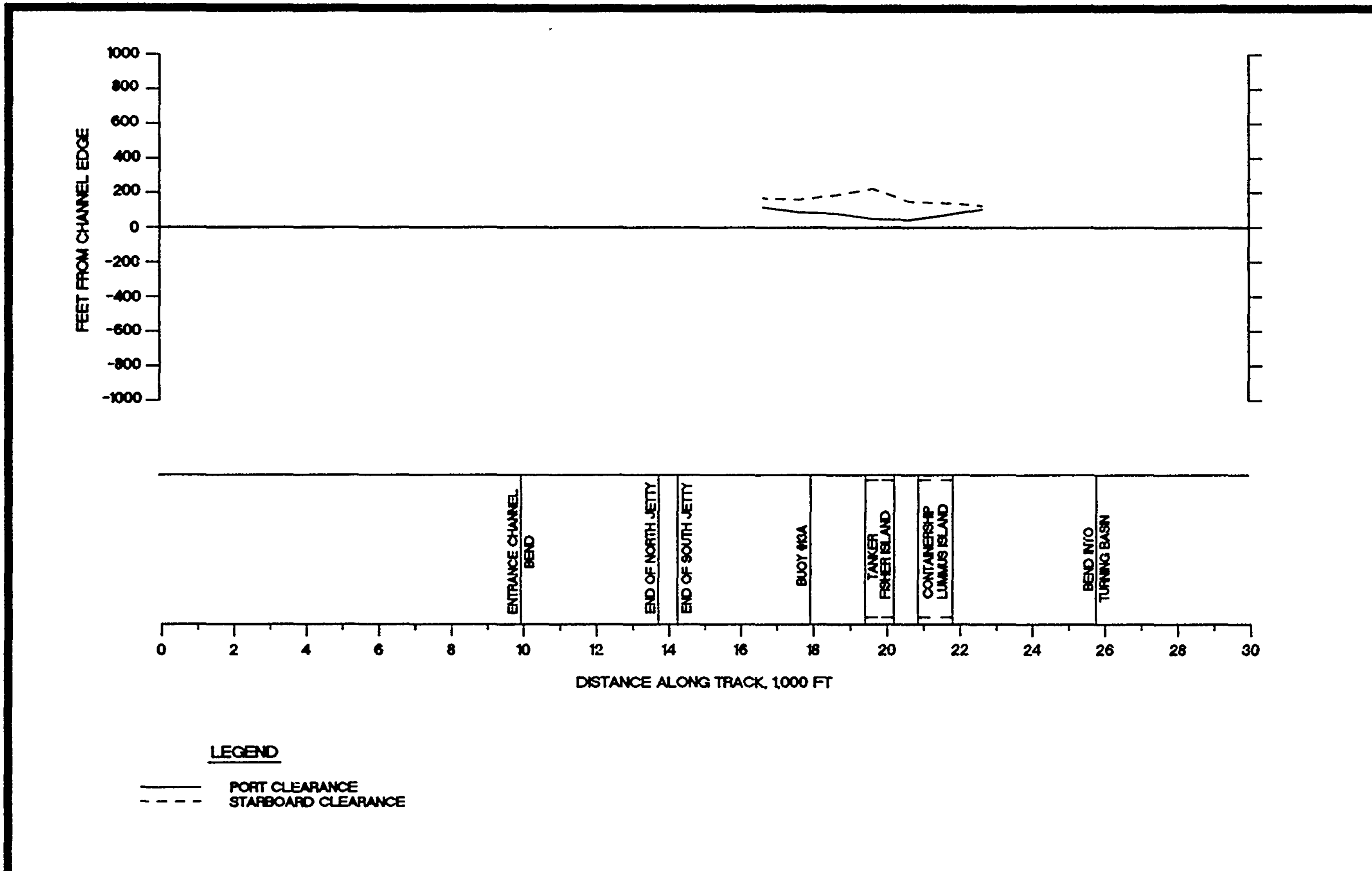


Figure 106. Port and starboard clearance, 1,000-ft channel sections, existing channel, 950-ft containership, flood tide, with wind, outbound, all runs

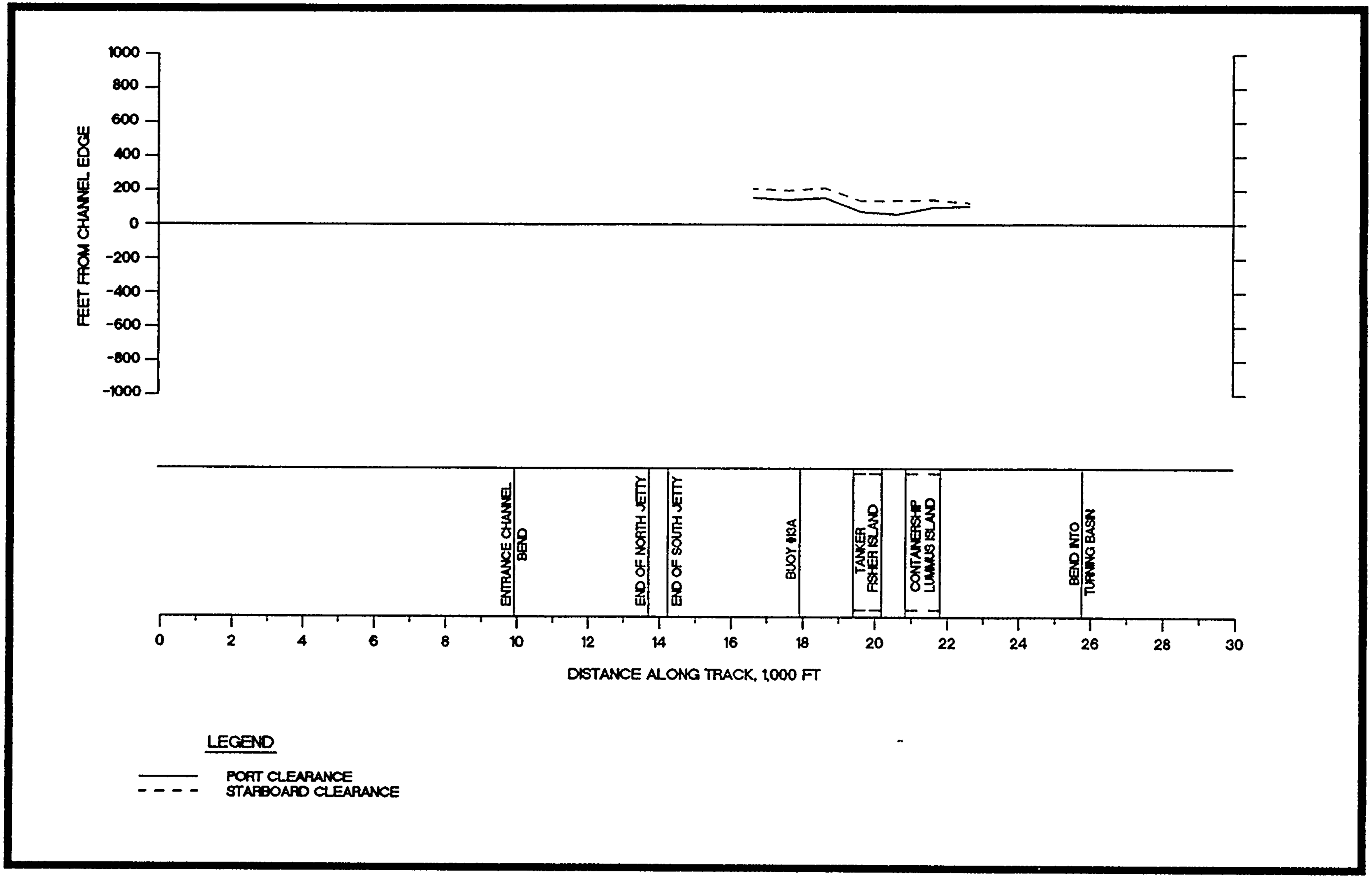


Figure 107. Port and starboard clearance, 1,000-ft channel sections, proposed channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

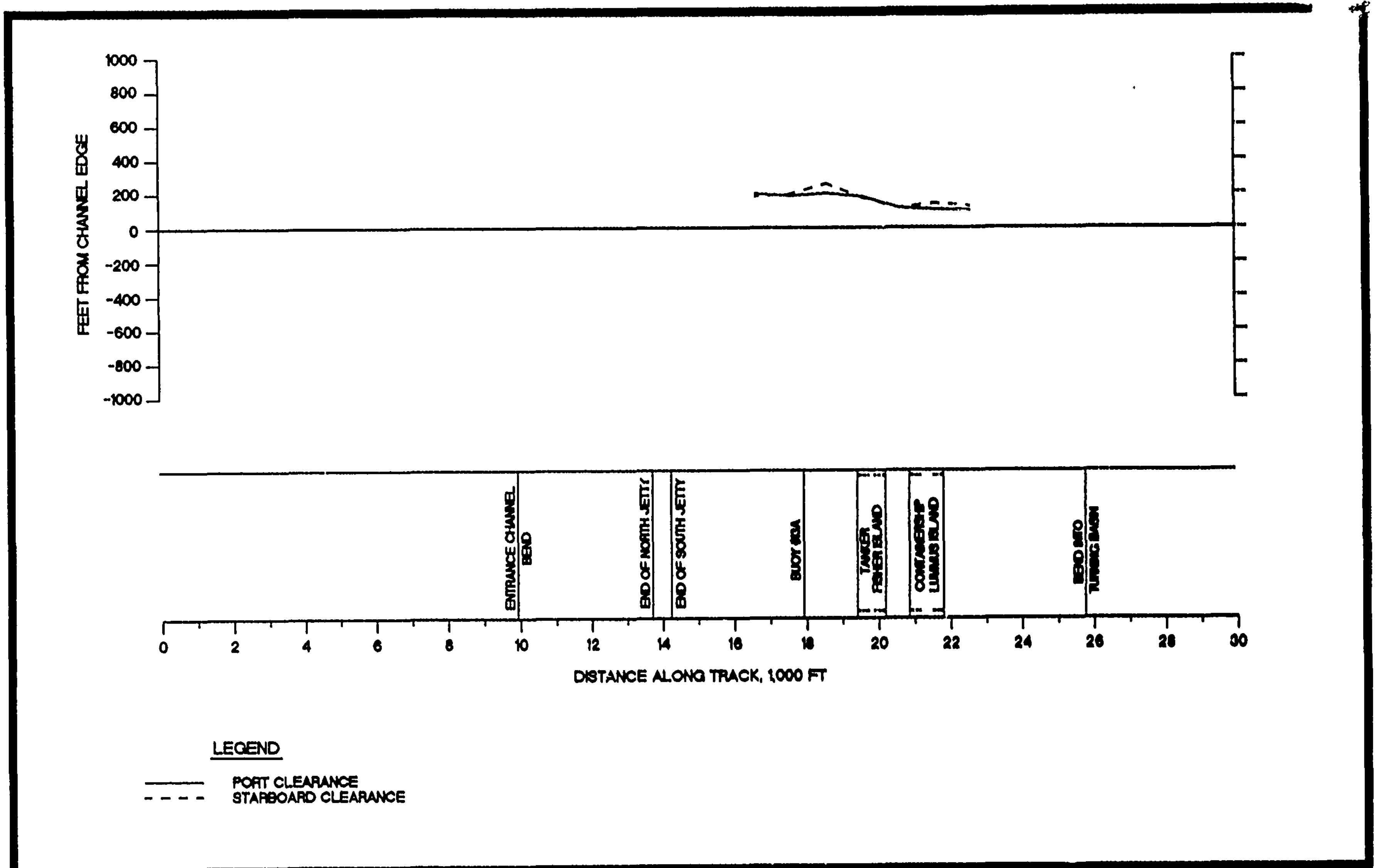


Figure 108. Port and starboard clearance, 1,000-ft channel sections, alternative channel, 950-ft containership, flood tide, 25-knot northeast wind, outbound, all runs

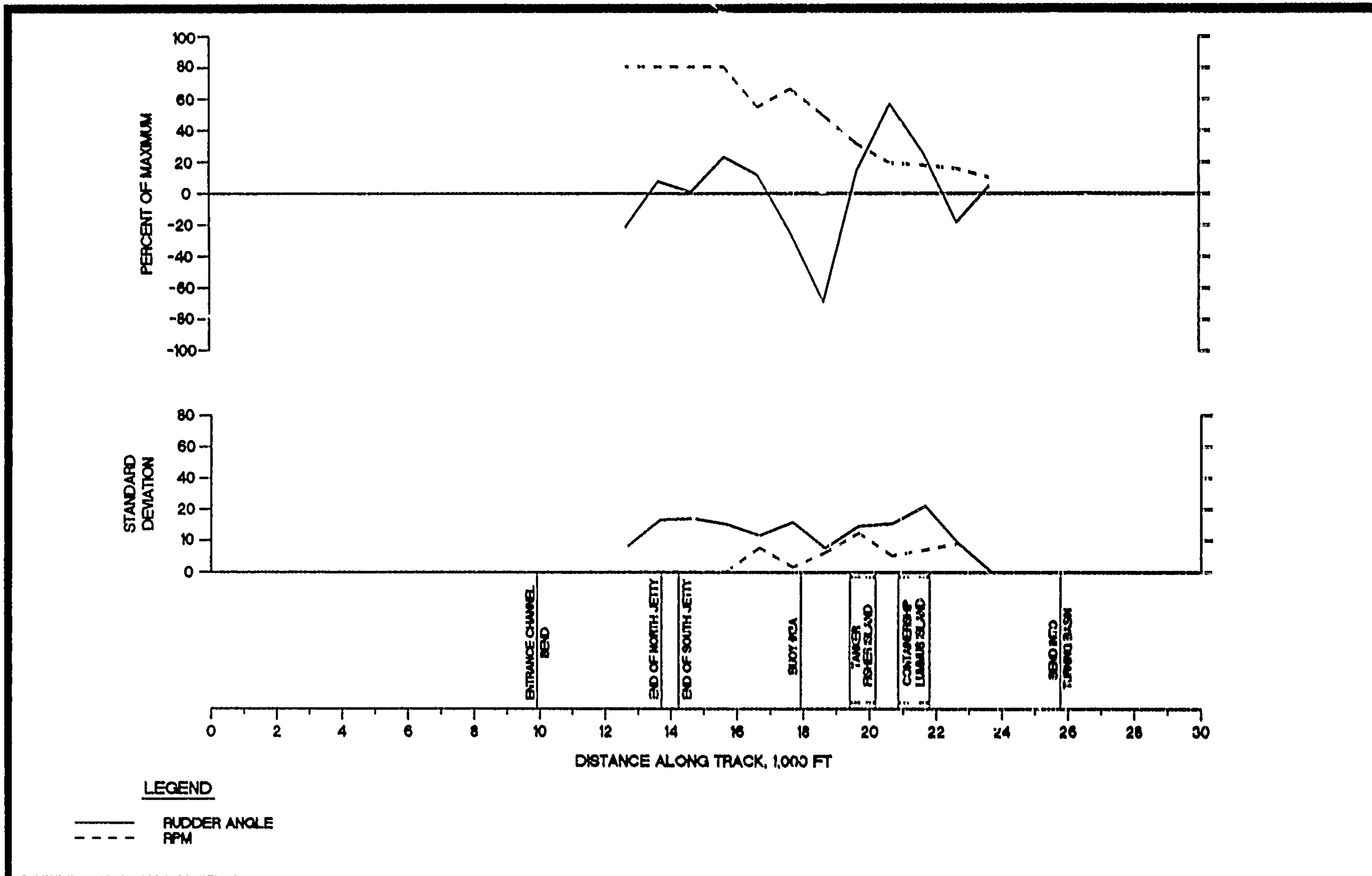


Figure 109. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, outbound, all runs

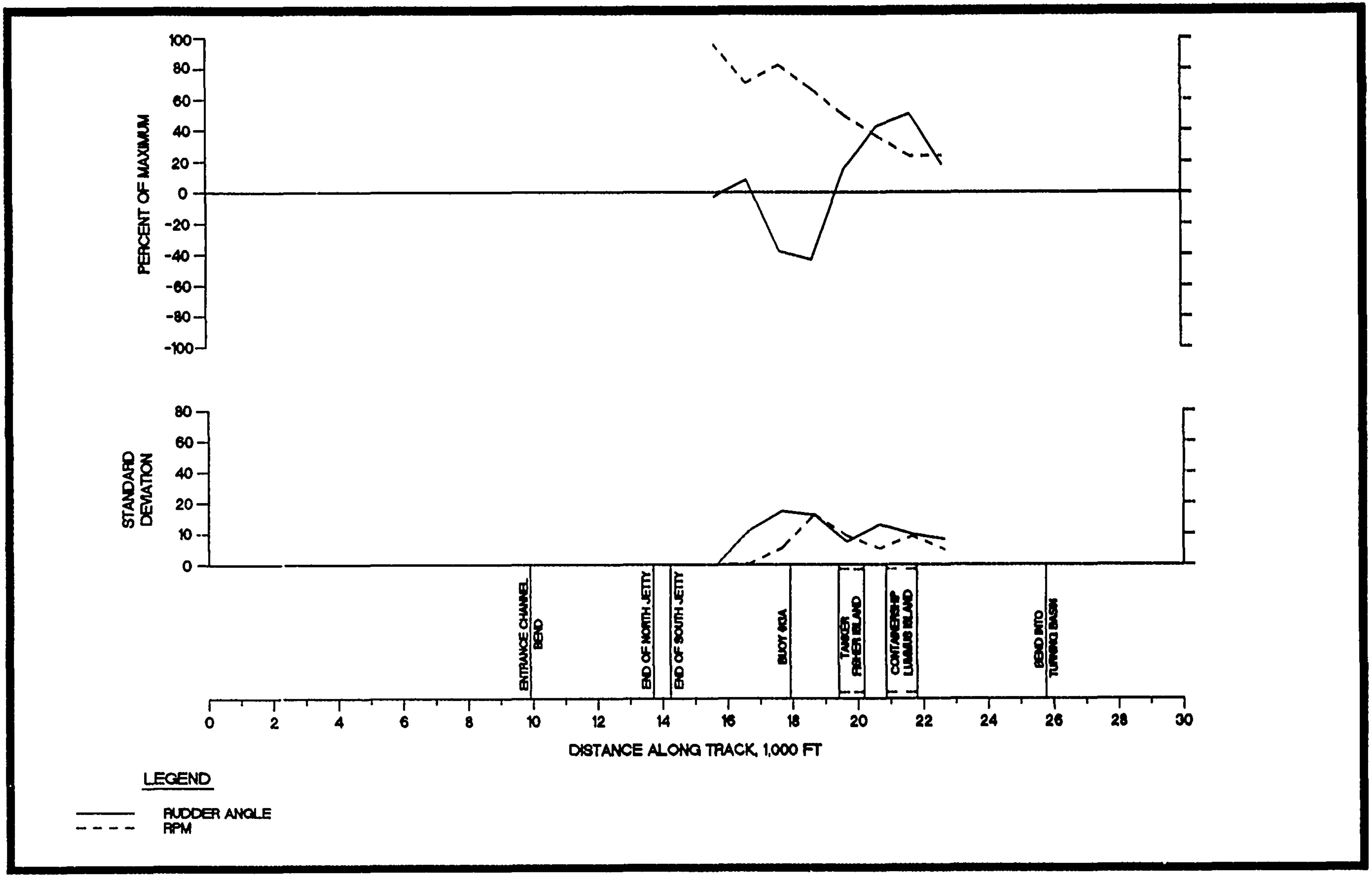


Figure 110. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

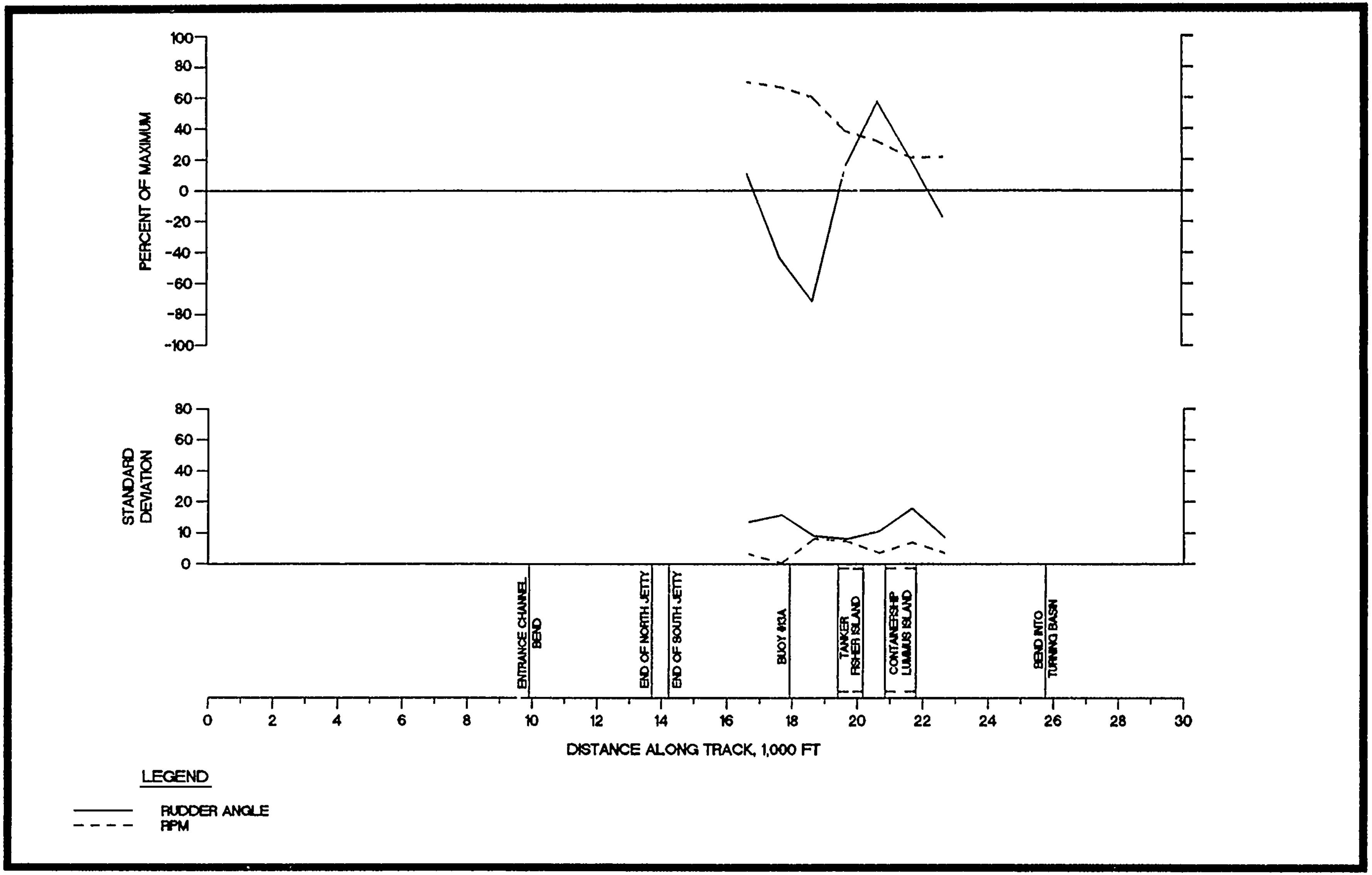


Figure 111. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, outbound, all runs

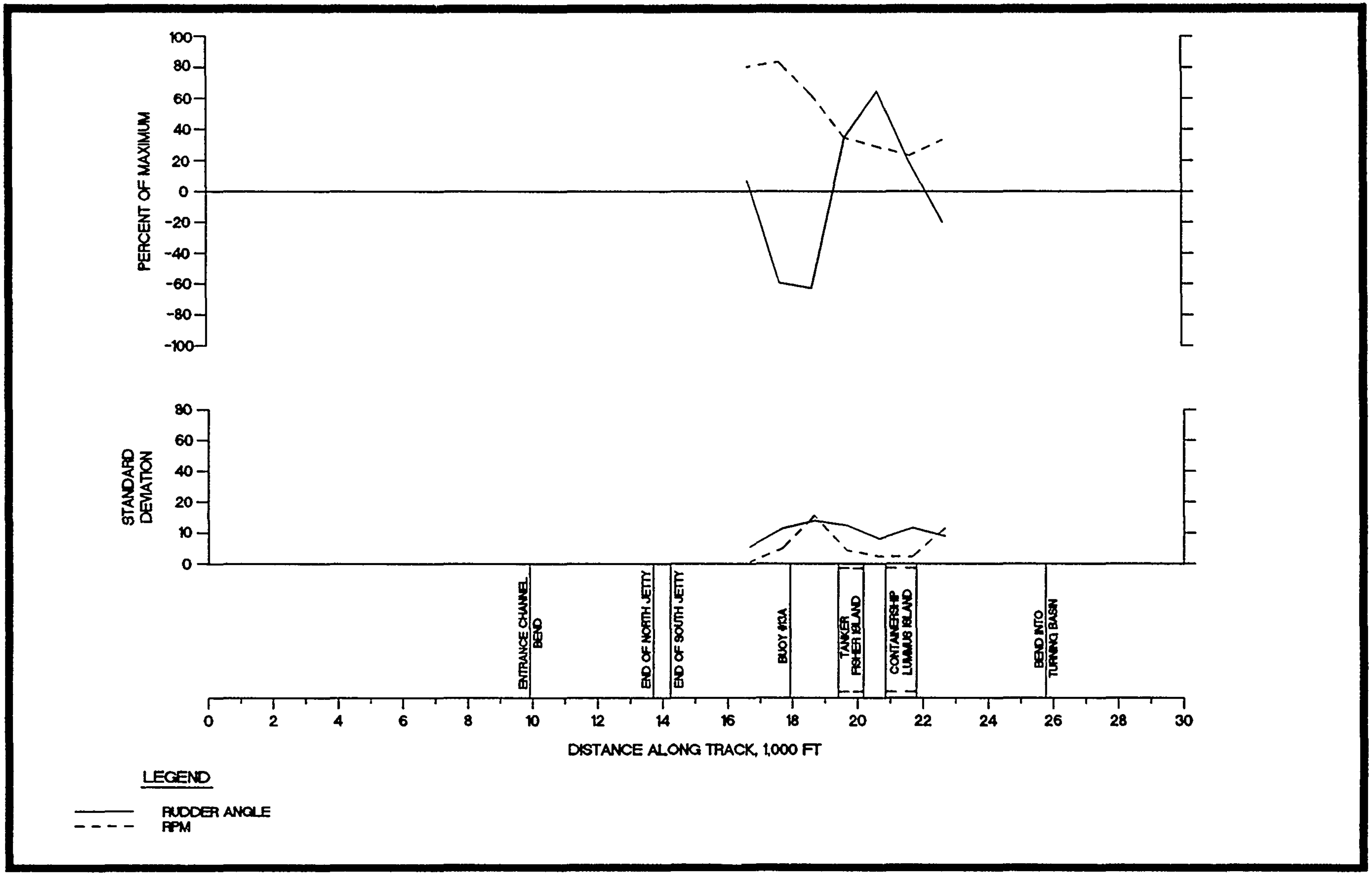


Figure 112. Rudder angle and rpm, 1,000-ft channel sections, proposed channel, 950-ft containership, ebb tide, outbound, all runs

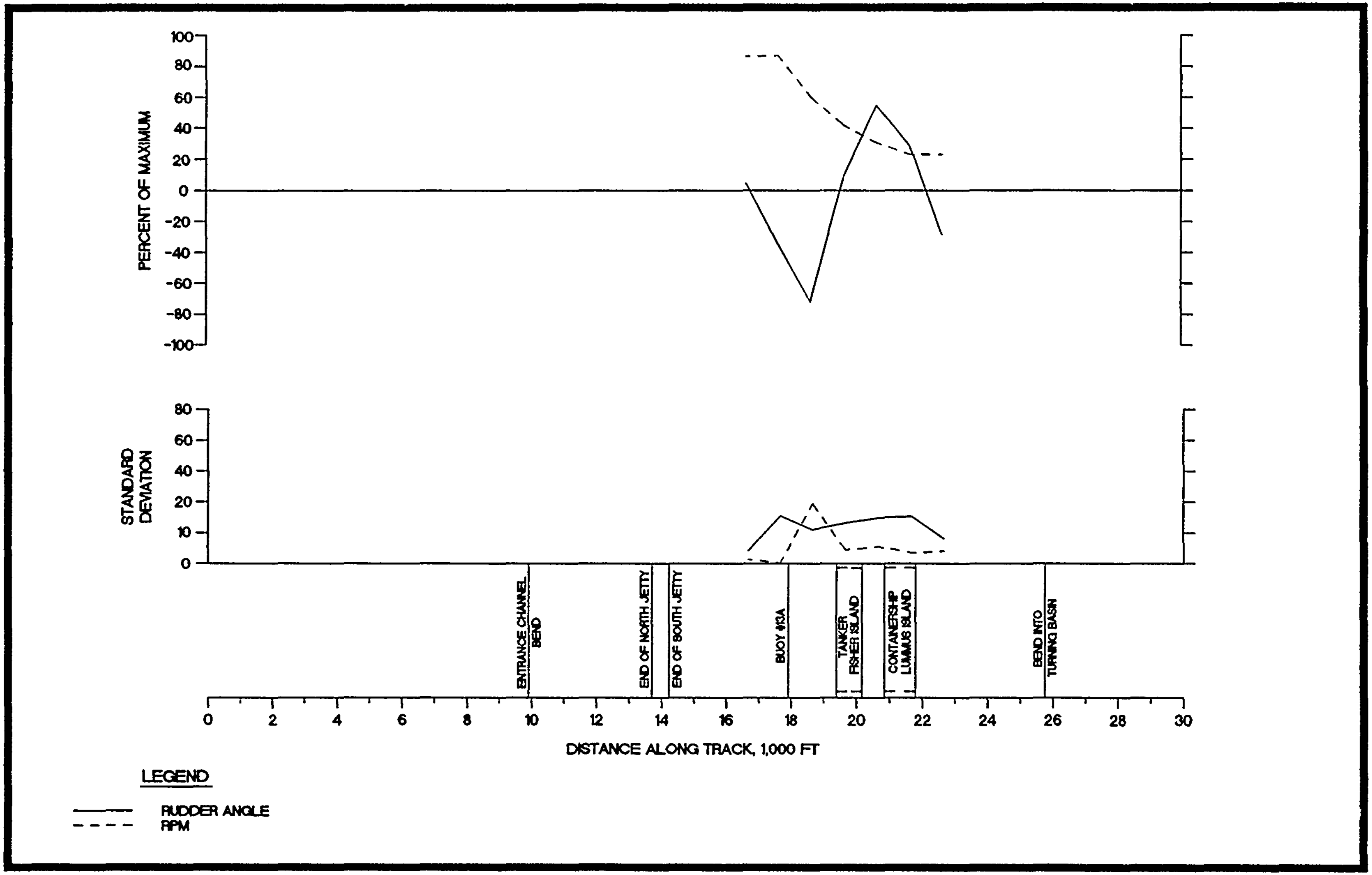


Figure 113. Rudder angle and rpm, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, outbound, all runs

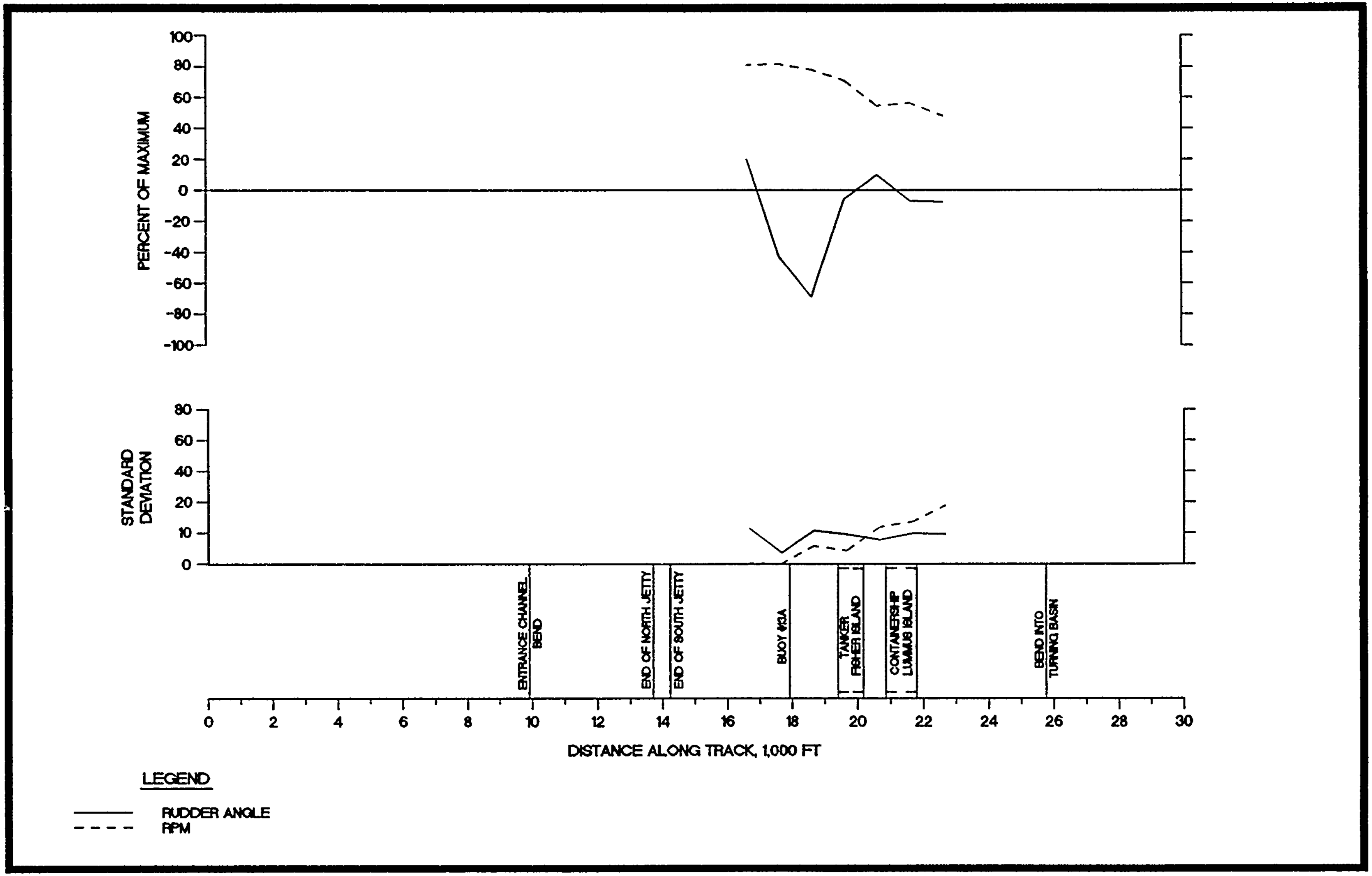


Figure 114. Rudder angle and rpm, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, with wind, outbound, all runs

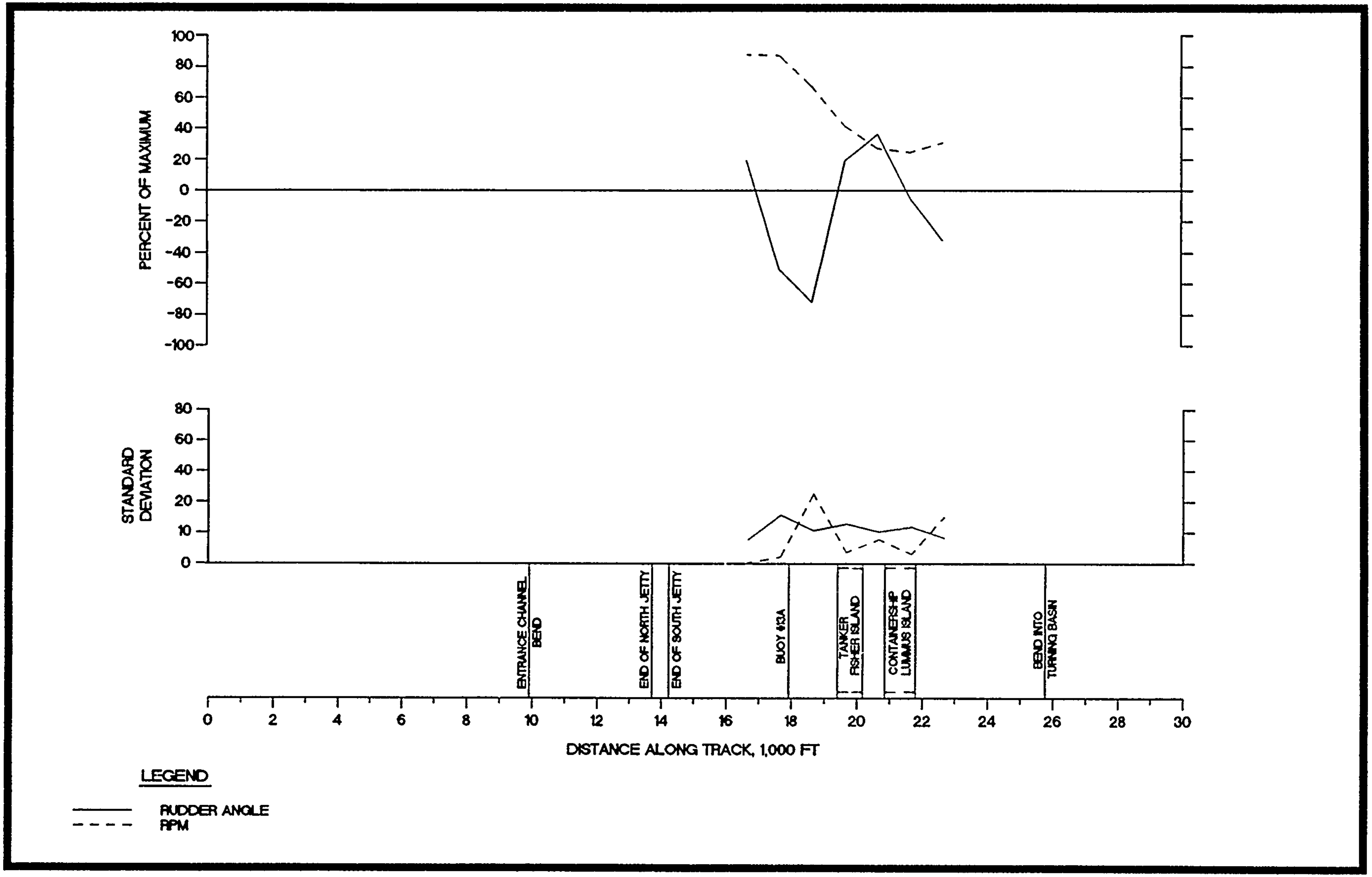


Figure 115. Rudder angle and rpm, 1,000-ft channel sections, proposed channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

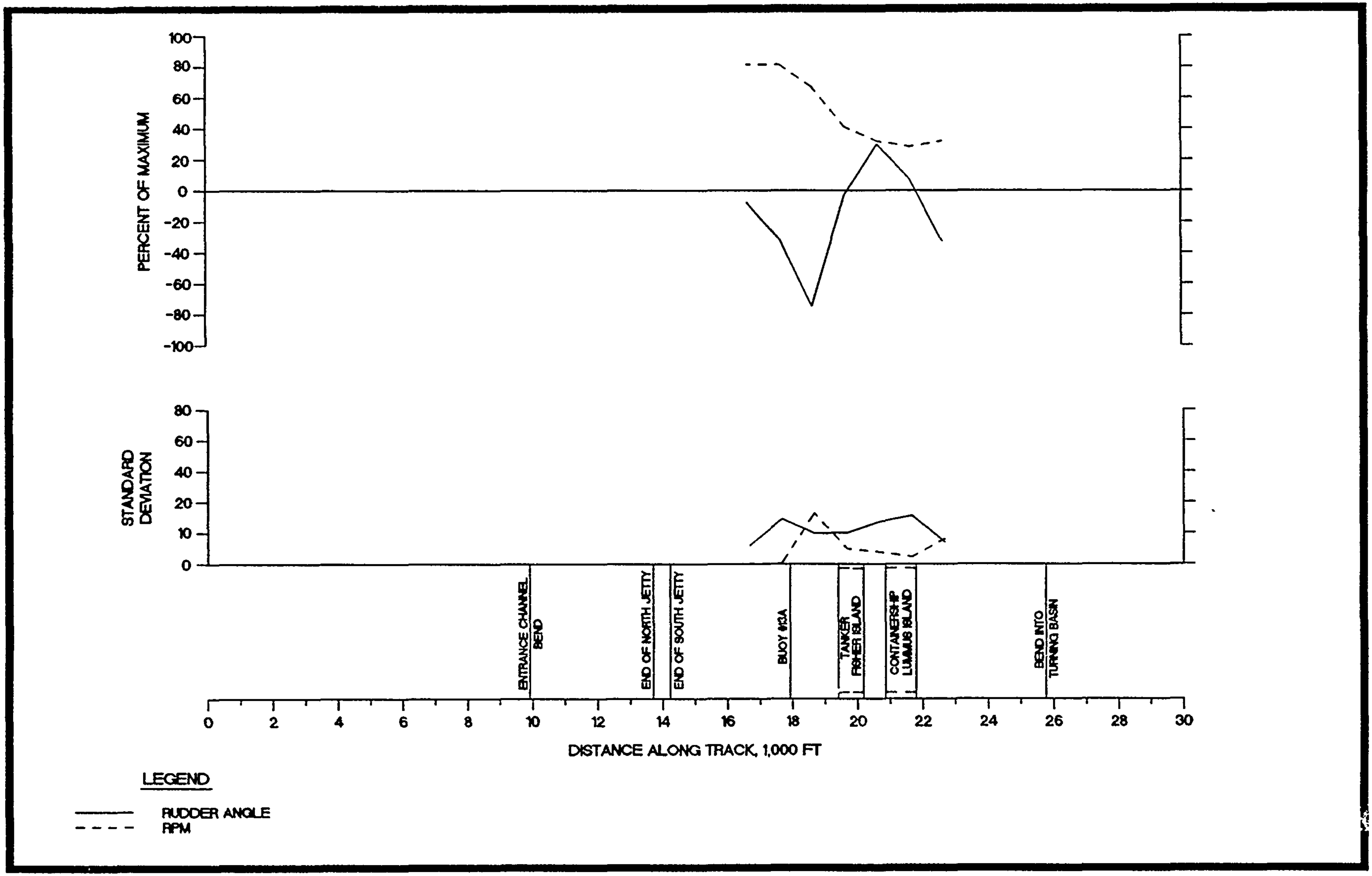


Figure 116. Rudder angle and rpm, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

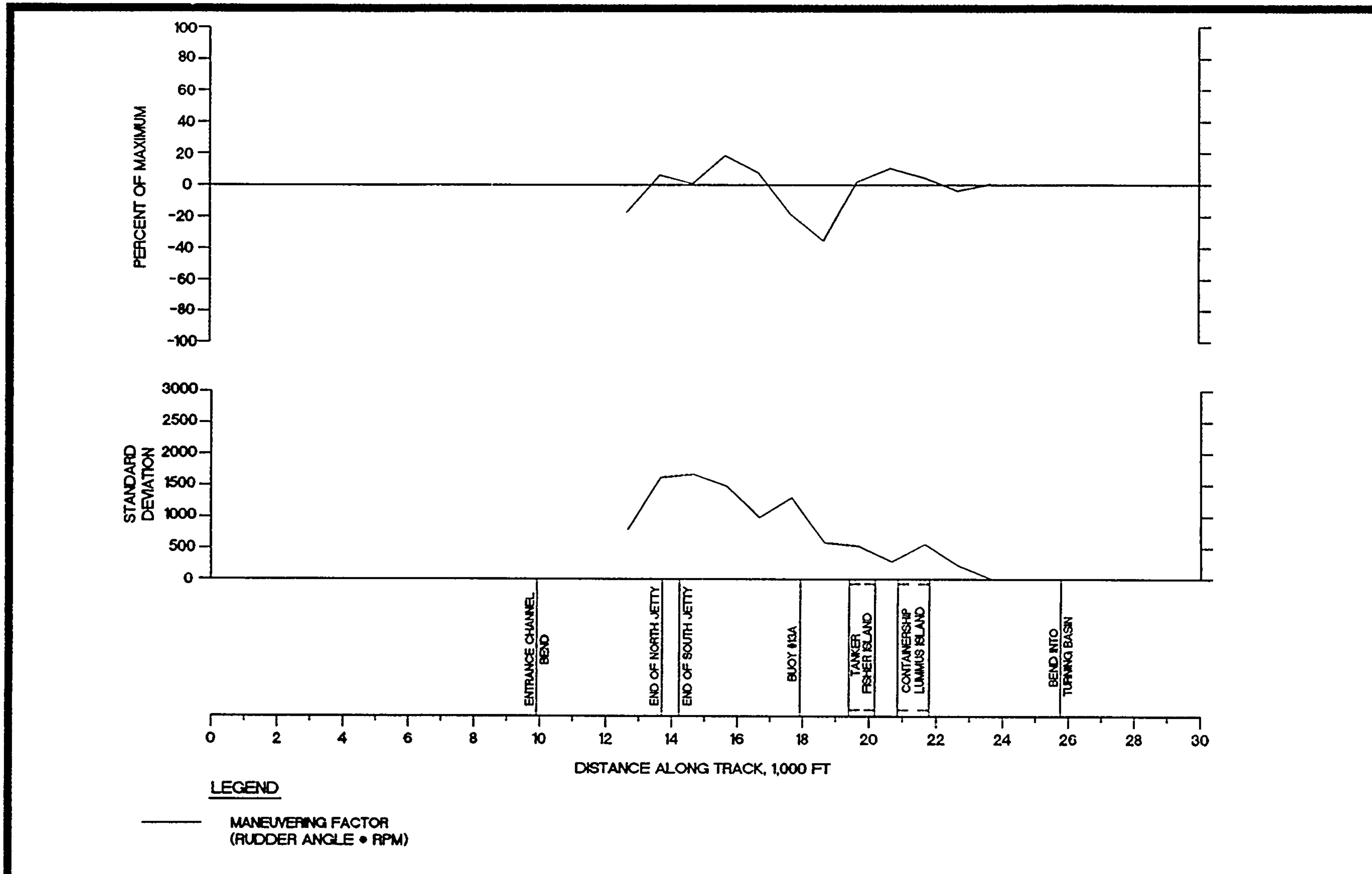


Figure 117. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, outbound, all runs

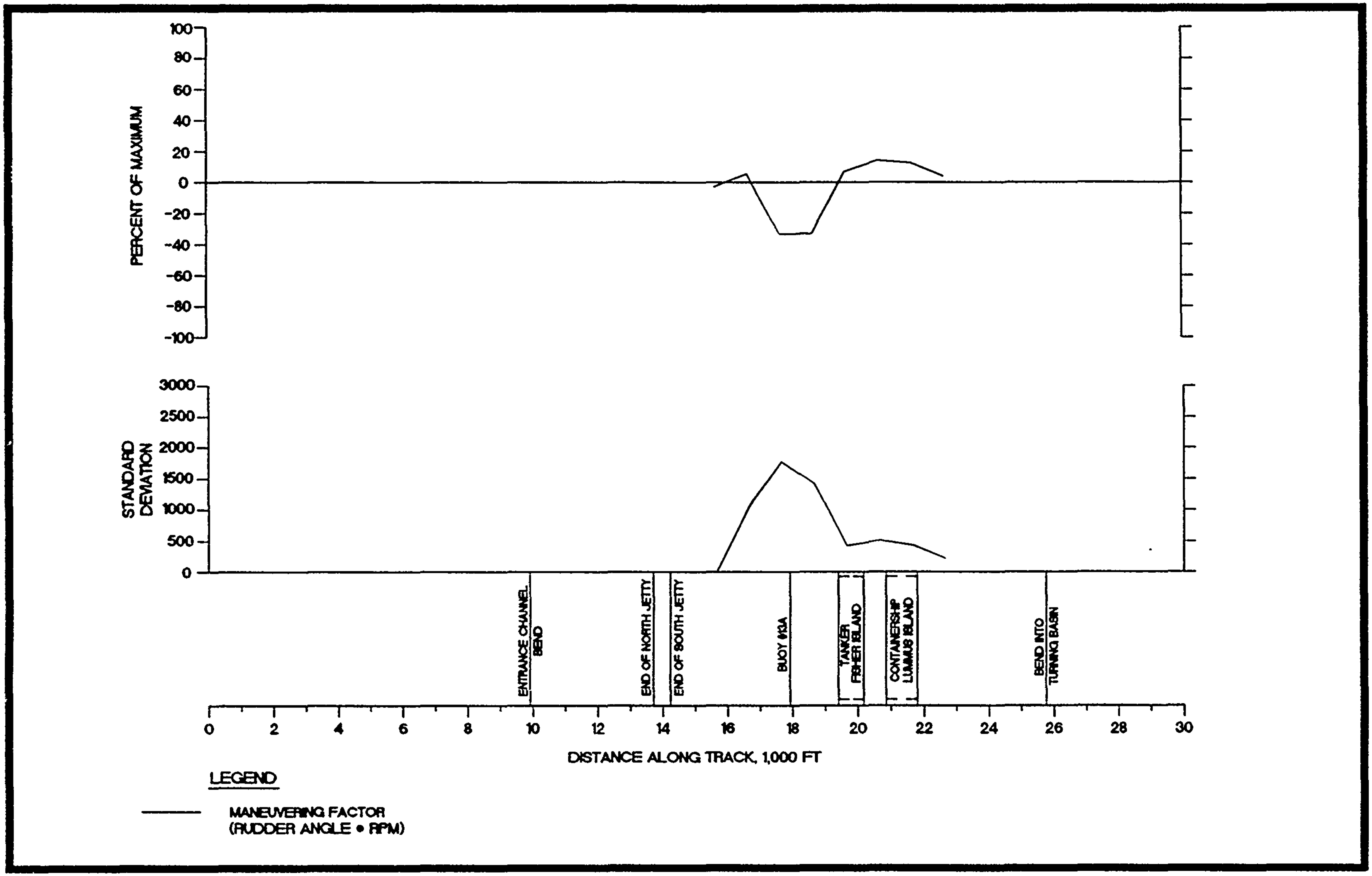


Figure 118. Maneuvering factor, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

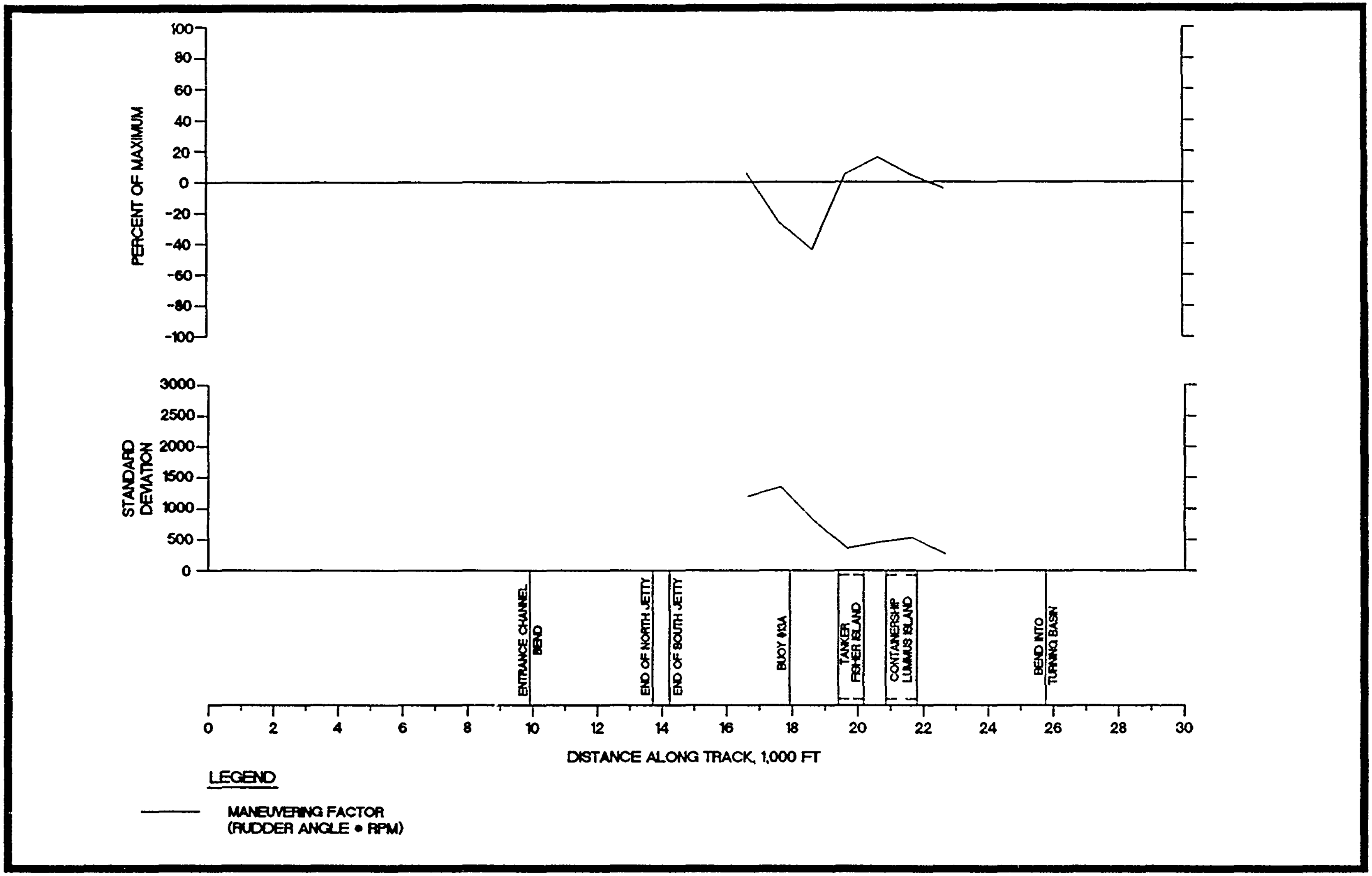


Figure 119. Maneuvering factor, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, outbound, all runs

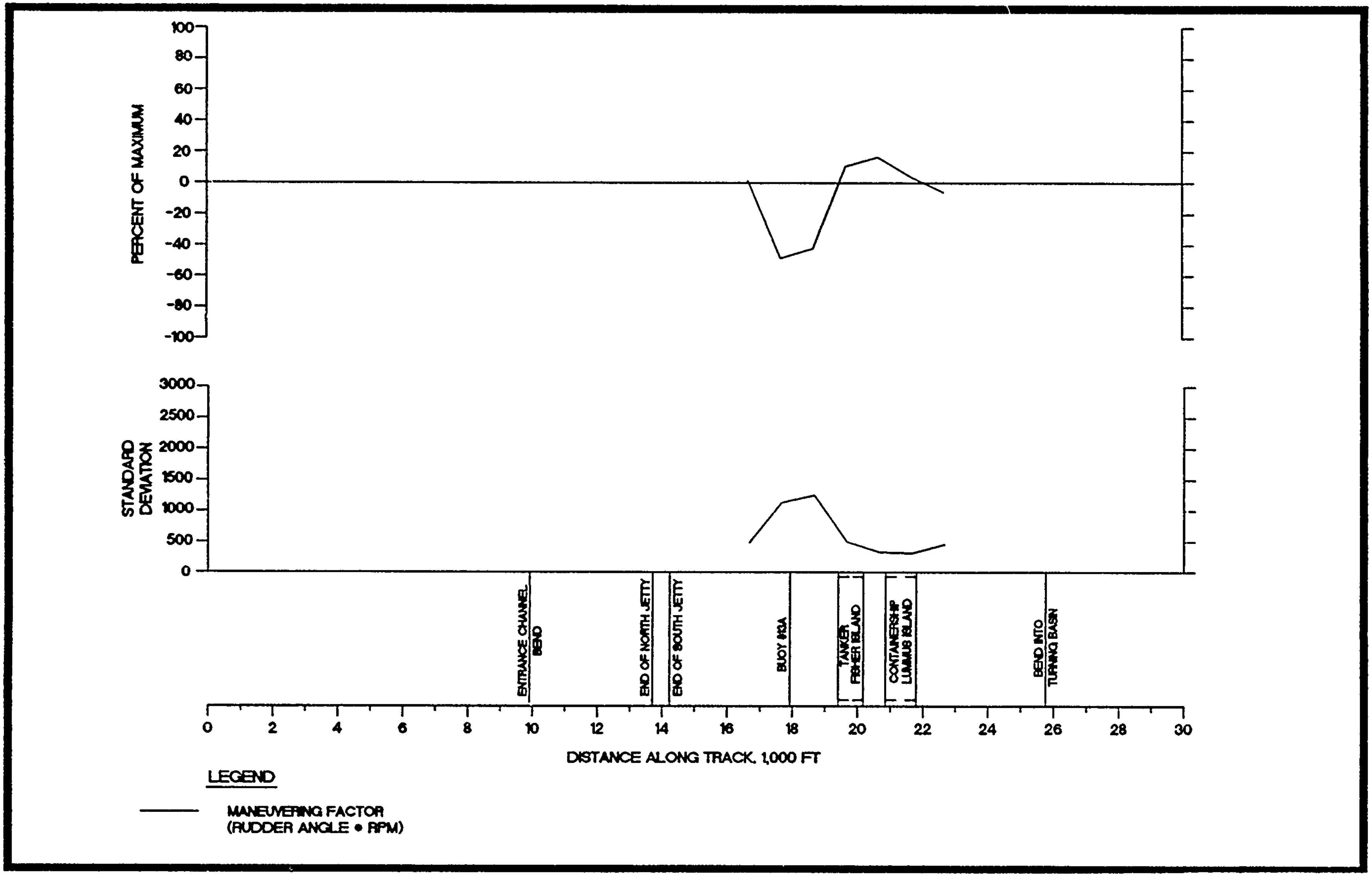


Figure 120. Maneuvering factor, 1,000-ft channel sections, proposed channel, 950-ft containership, ebb tide, outbound, all runs

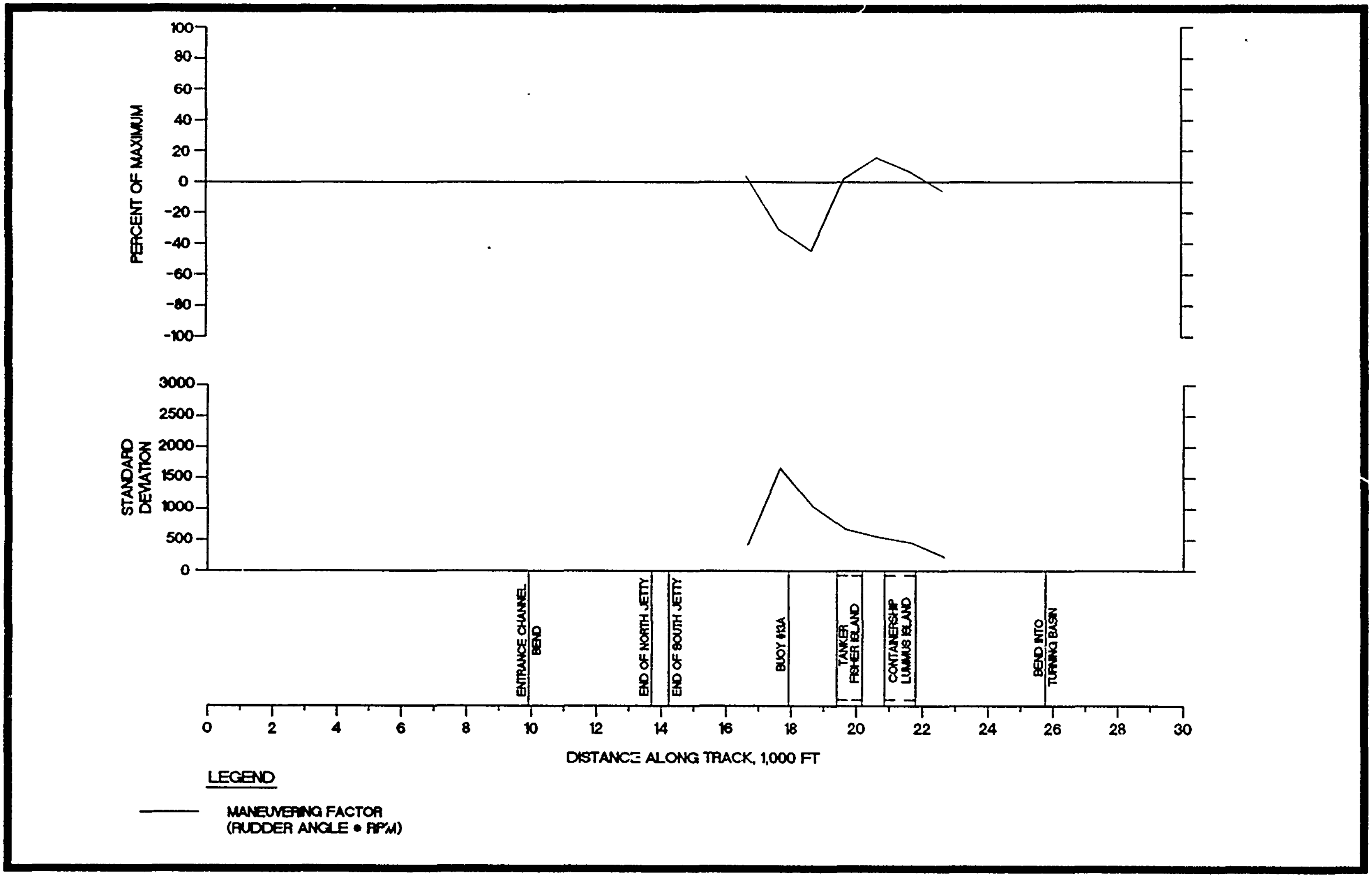


Figure 121. Maneuvering factor, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, outbound, all runs

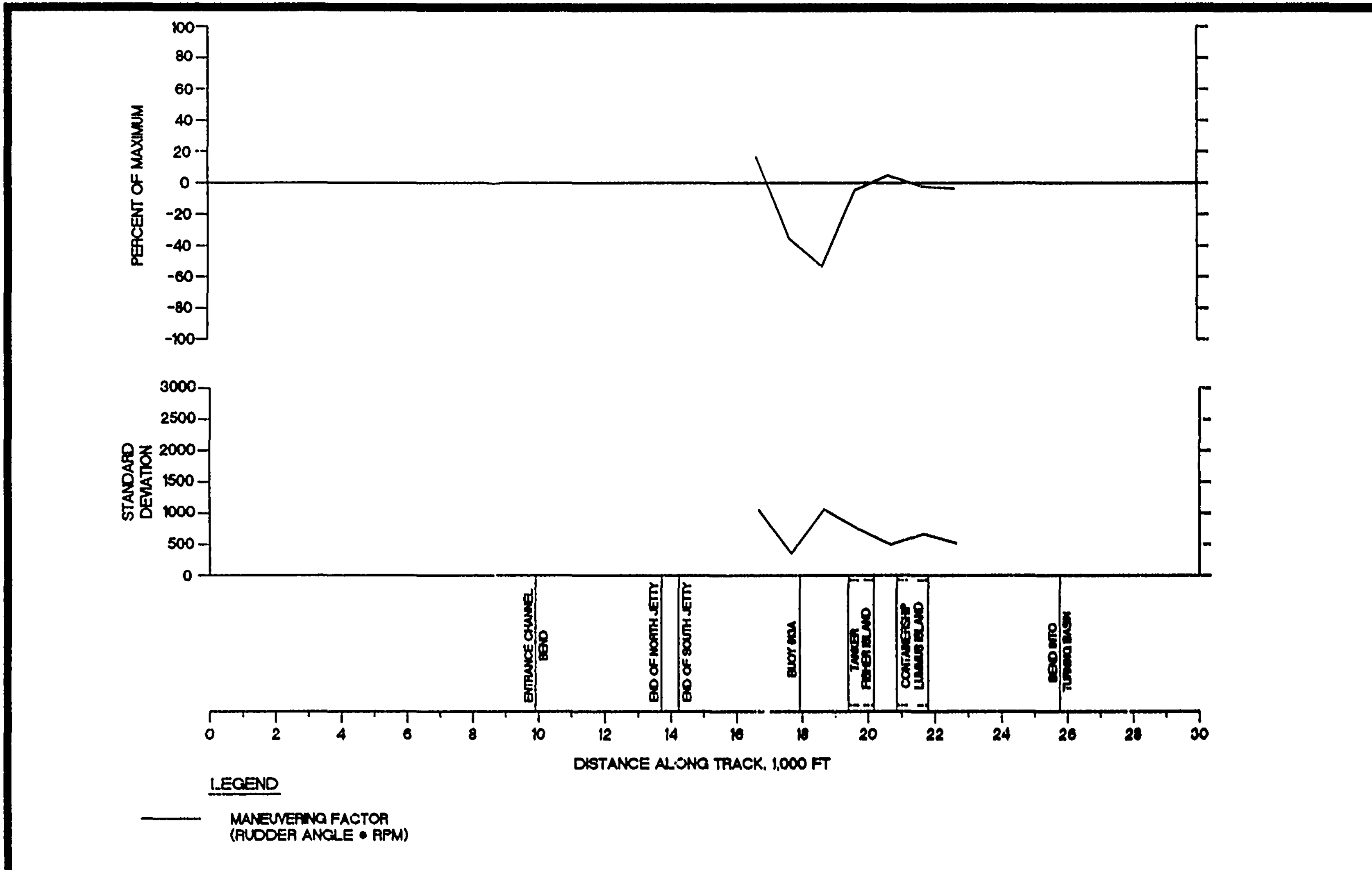


Figure 122. Maneuvering factor, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, with wind, outbound, all runs

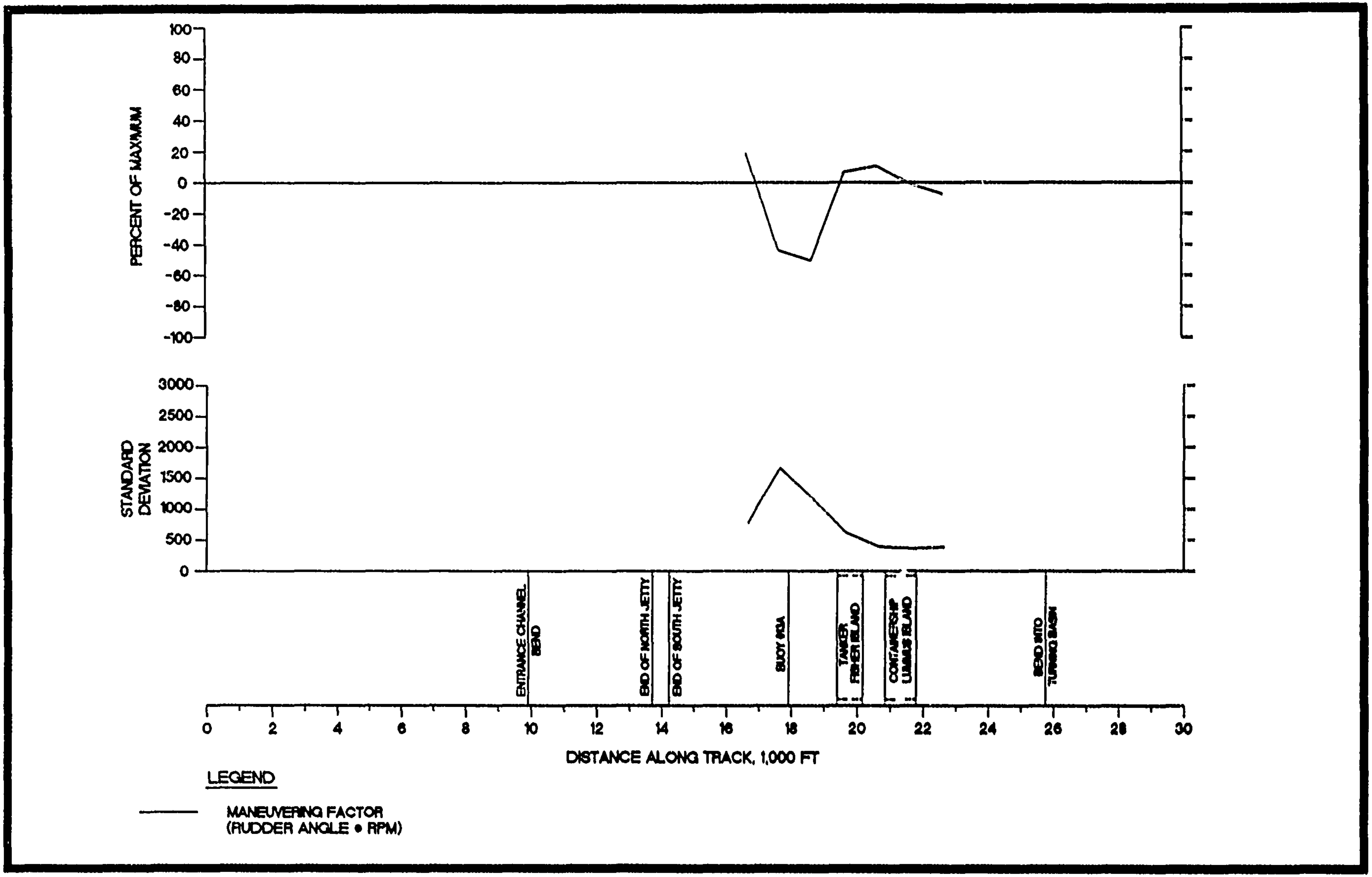


Figure 123. Maneuvering factor, 1,000-ft channel sections, proposed channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

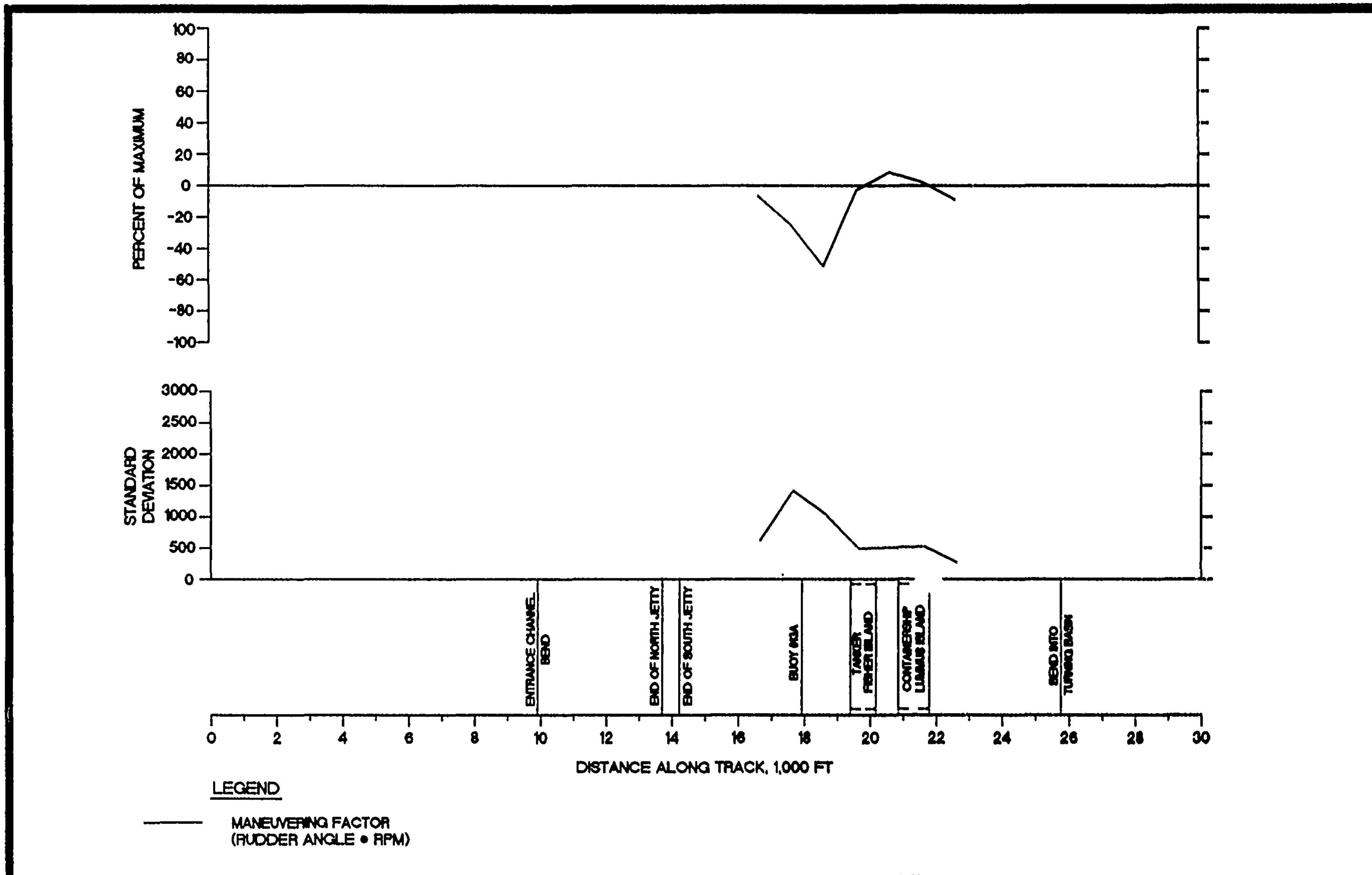


Figure 124. Maneuvering factor, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

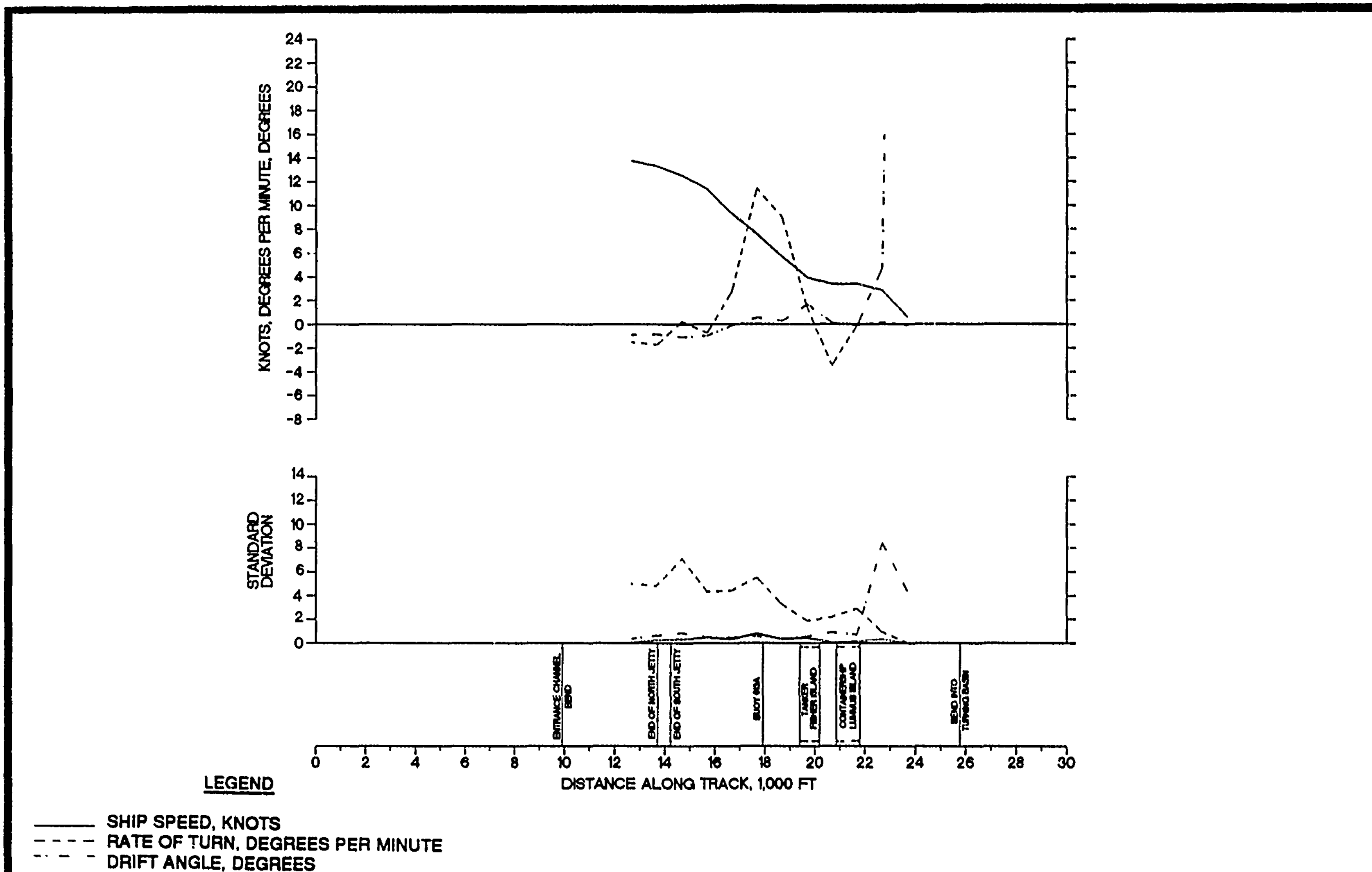


Figure 125. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, outbound, all runs

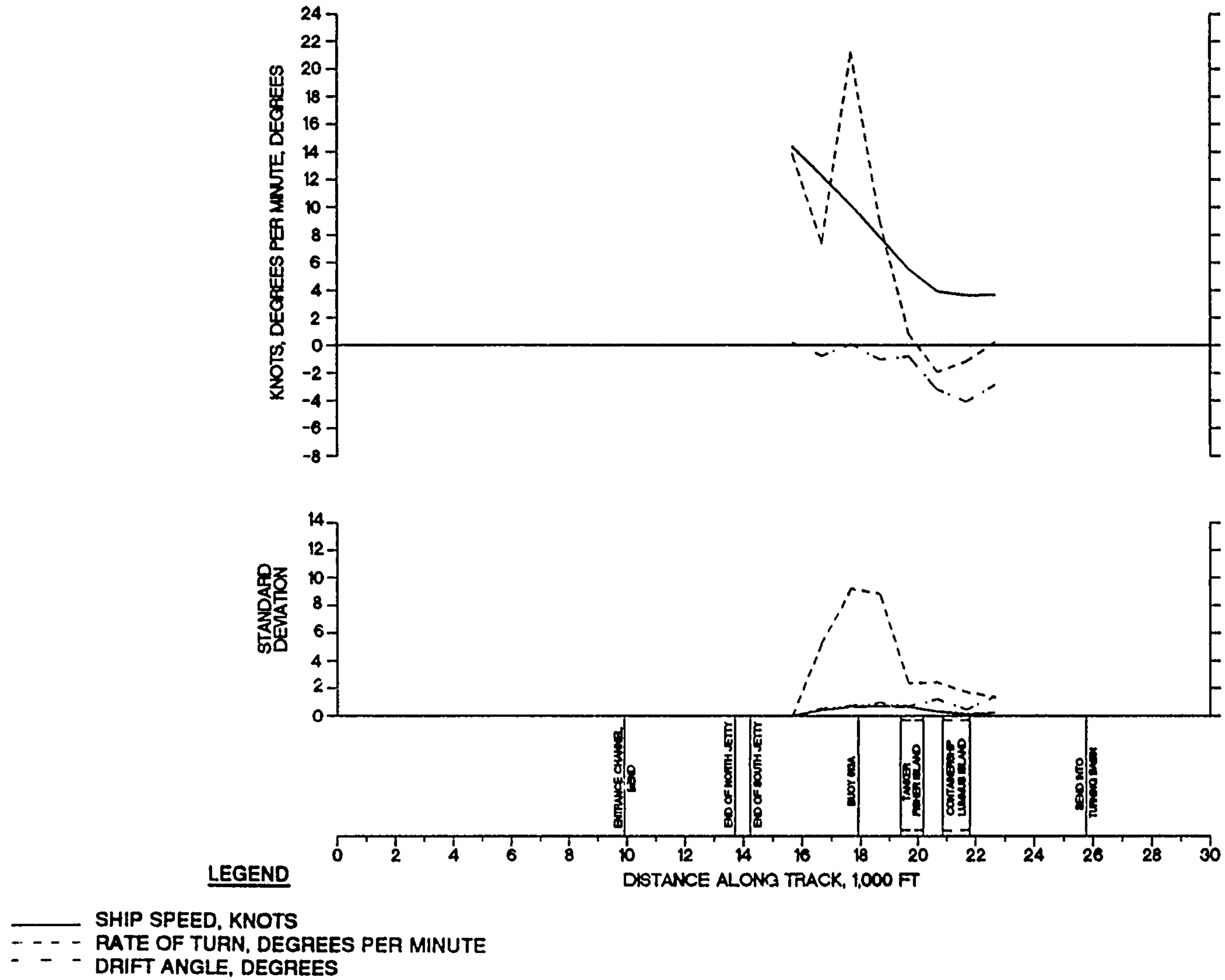


Figure 126. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

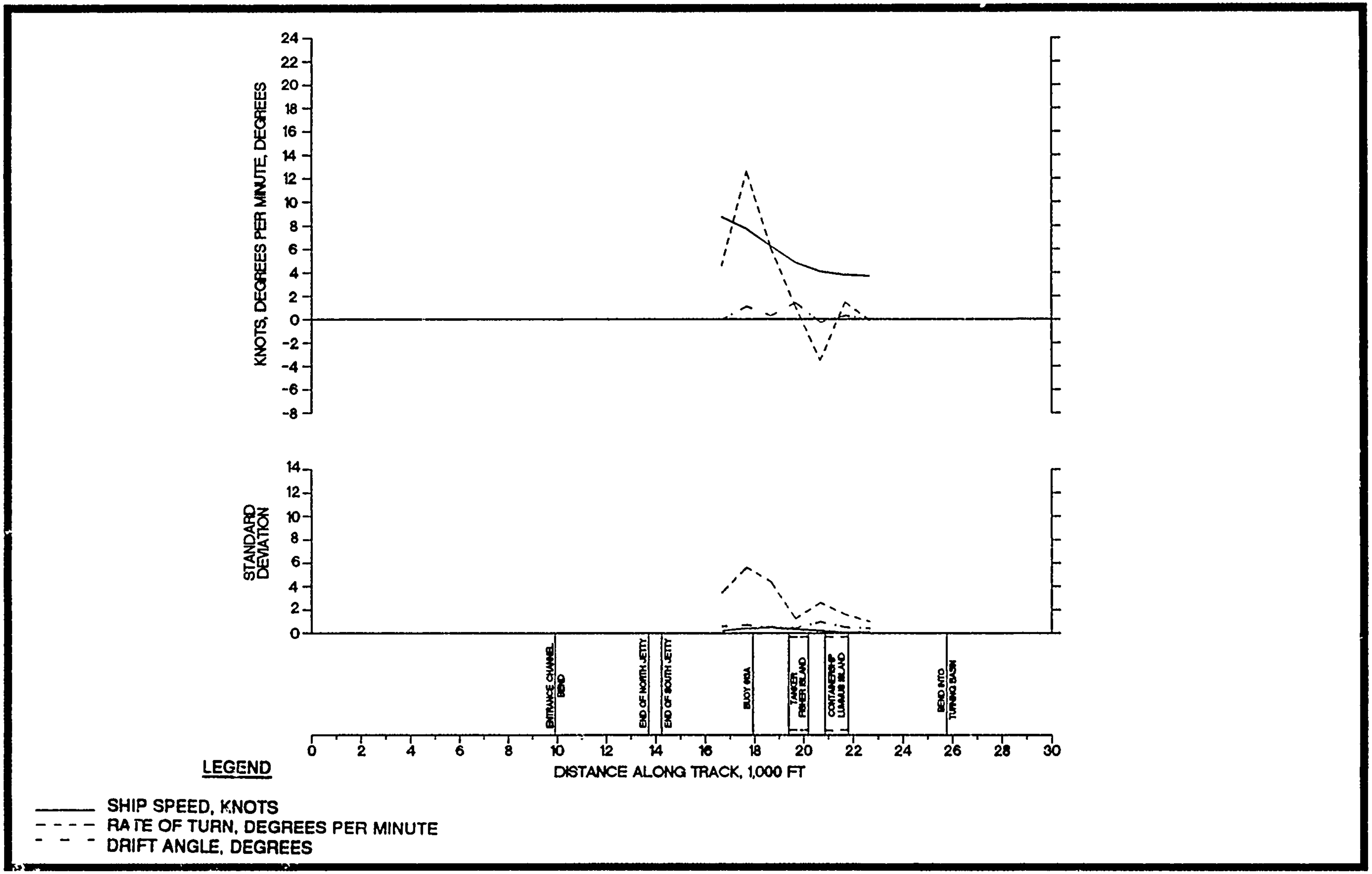


Figure 127. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, outbound, all runs

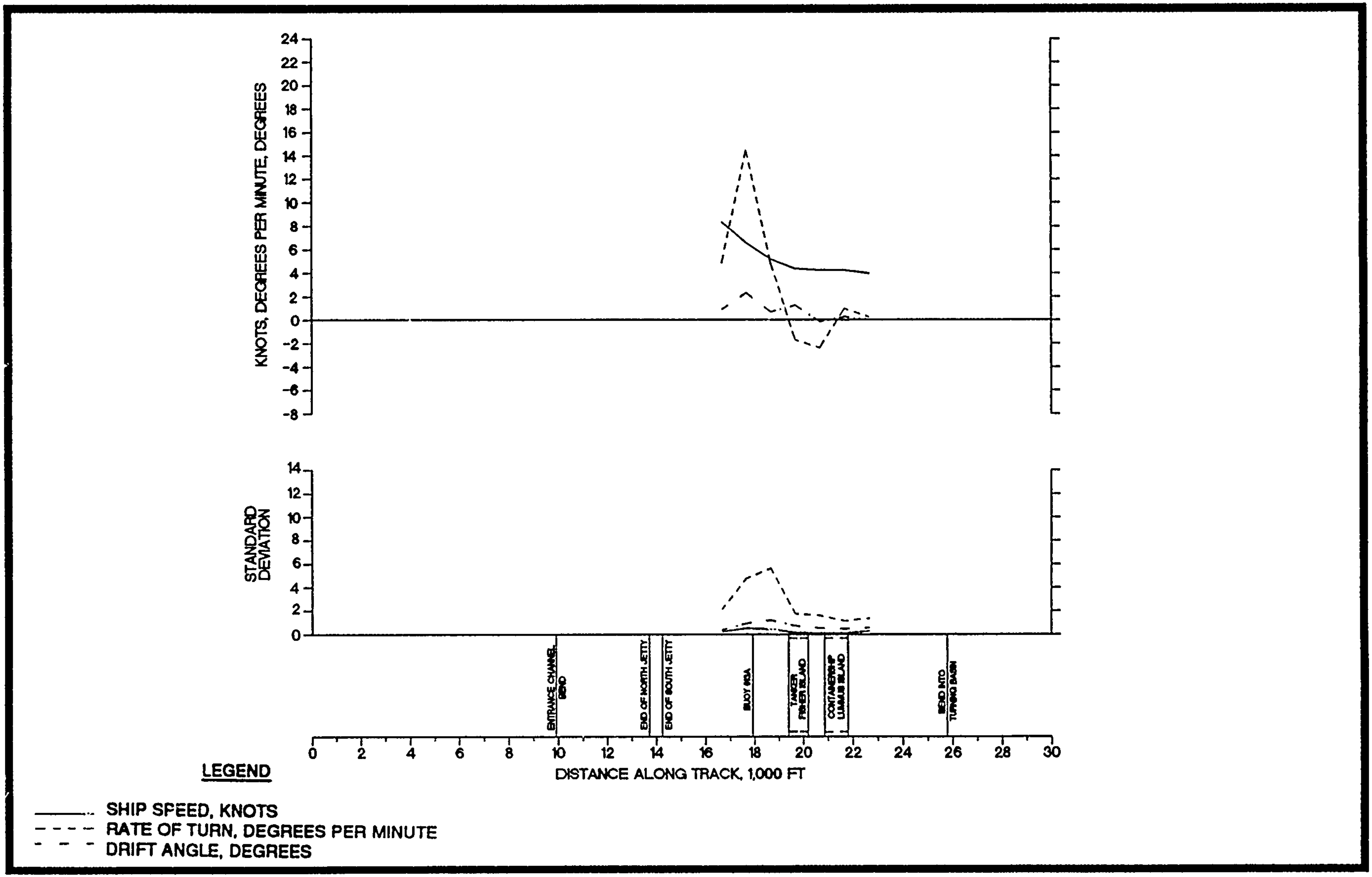


Figure 128. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, proposed channel, 950-ft containership, ebb tide, outbound, all runs

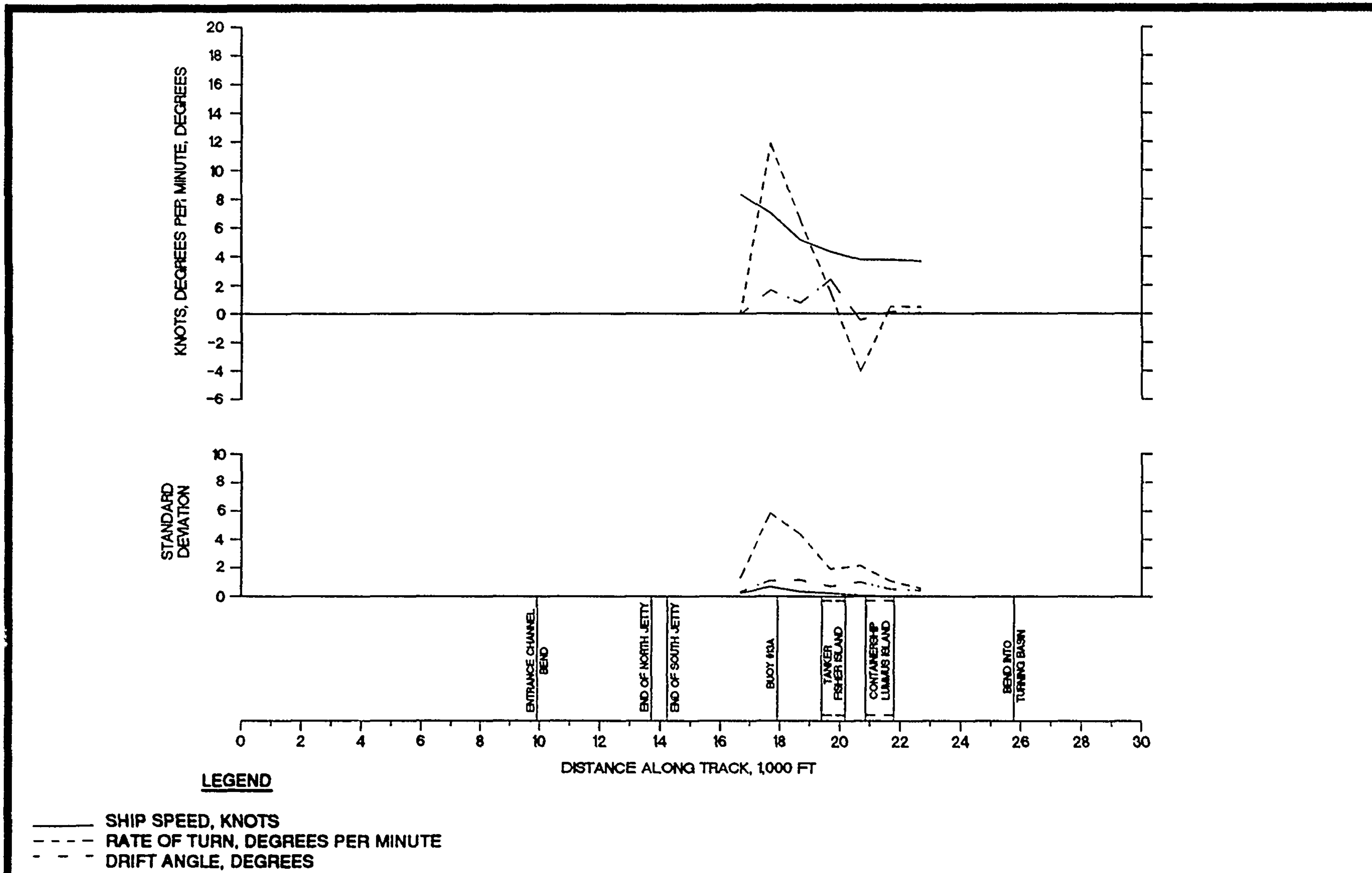


Figure 129. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, outbound, all runs

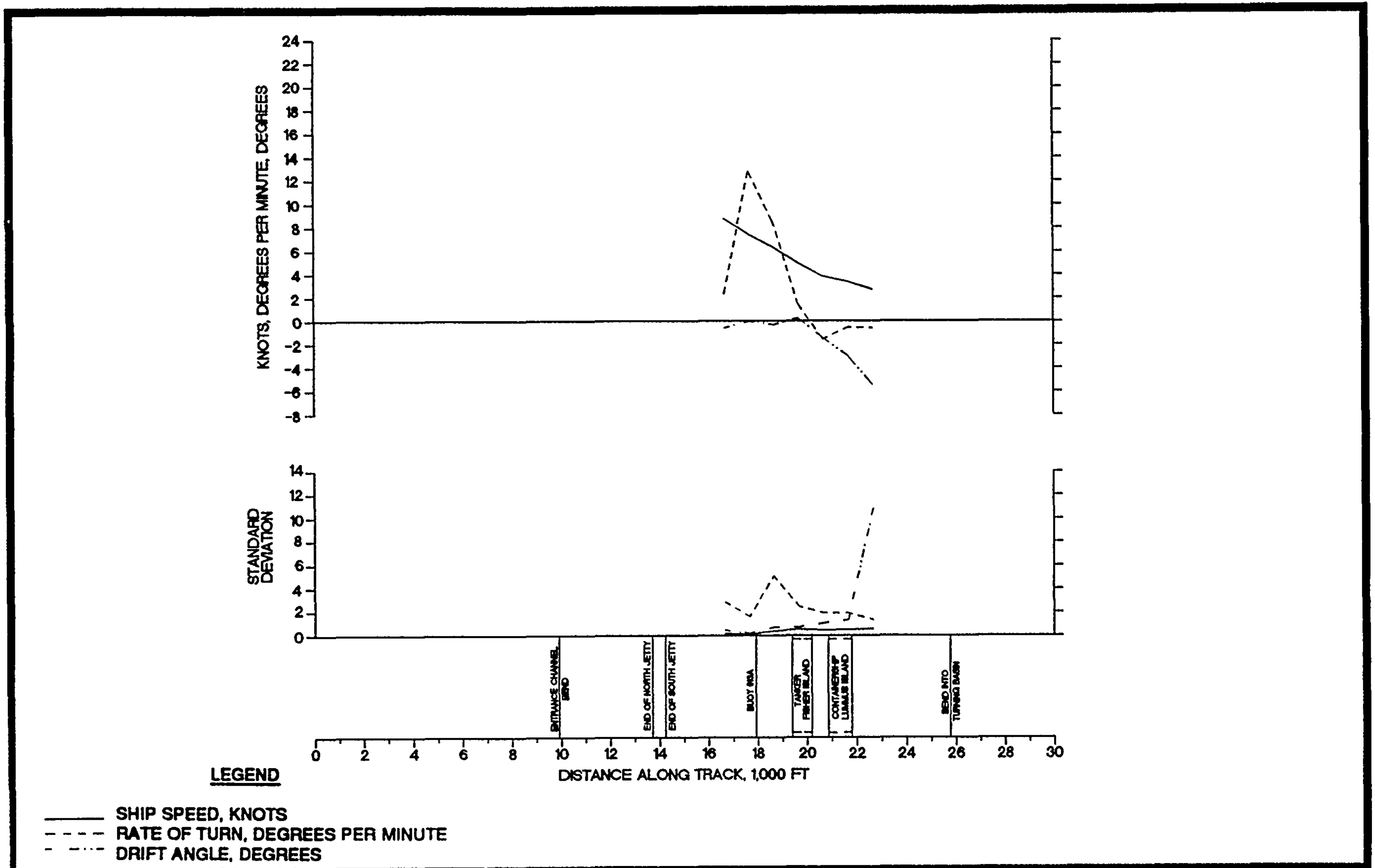


Figure 130. Ship speed rate of turn, drift angle, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, with wind, outbound, all runs

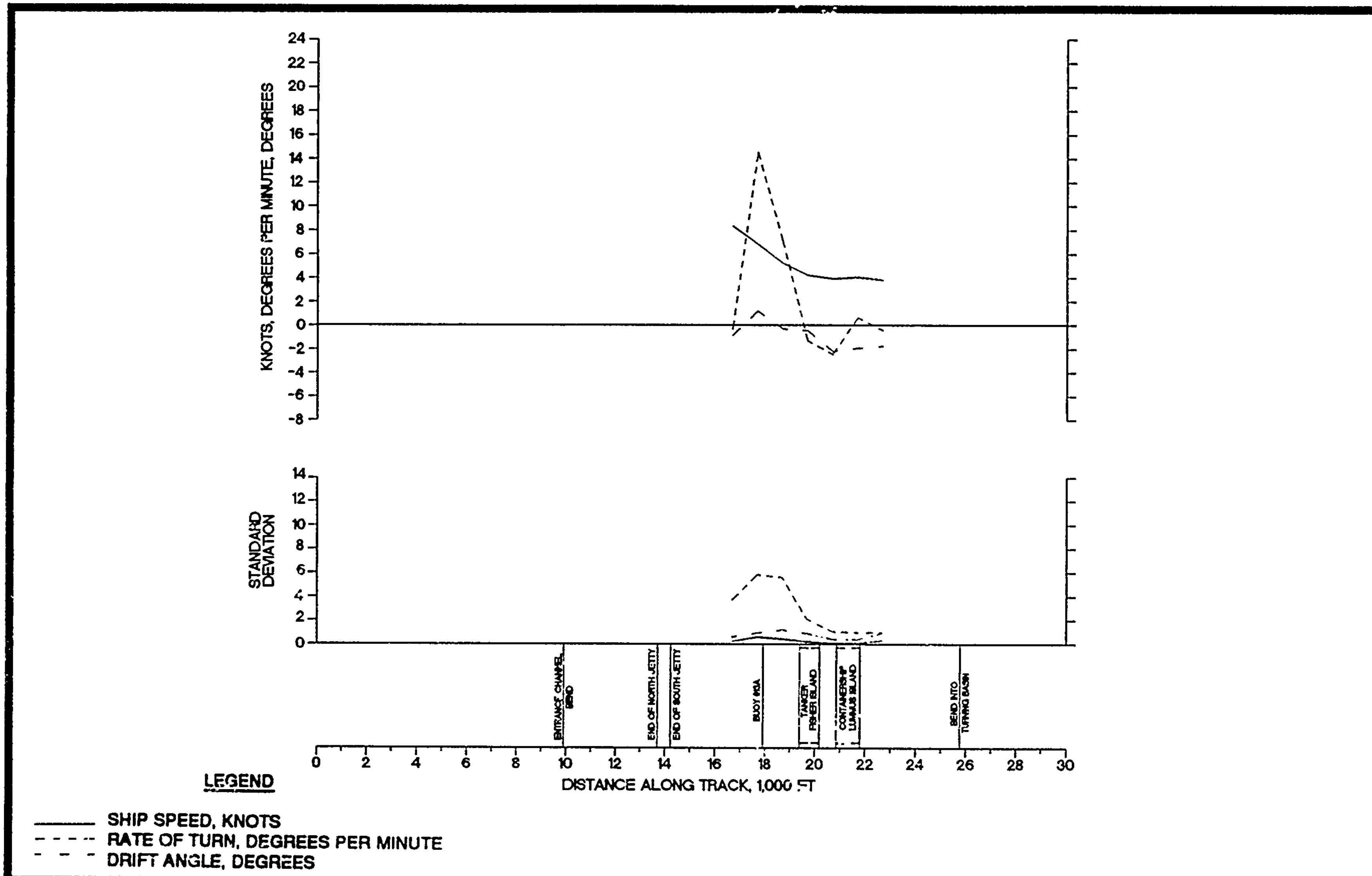


Figure 131. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, proposed channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

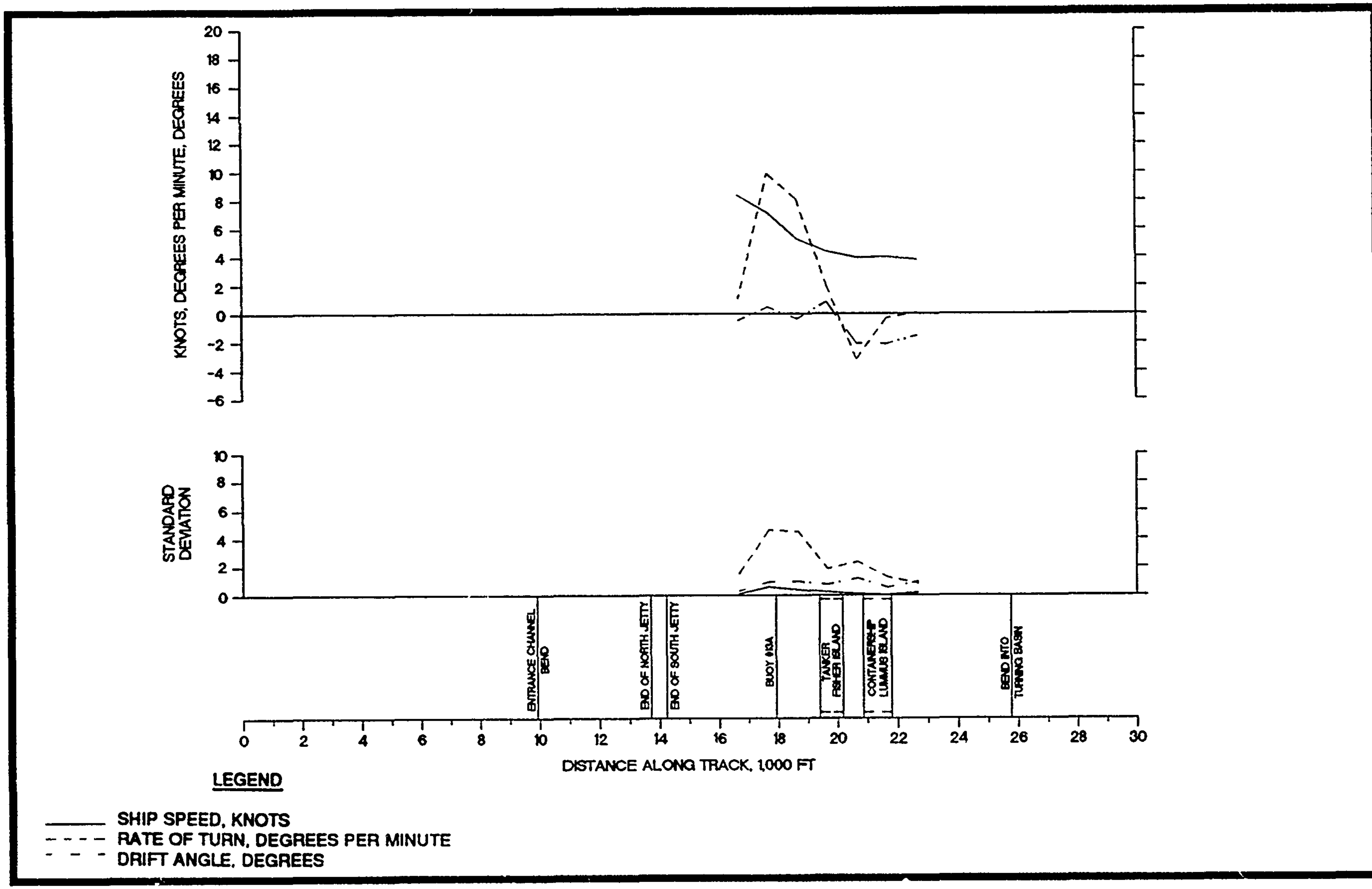


Figure 132. Ship speed, rate of turn, drift angle, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

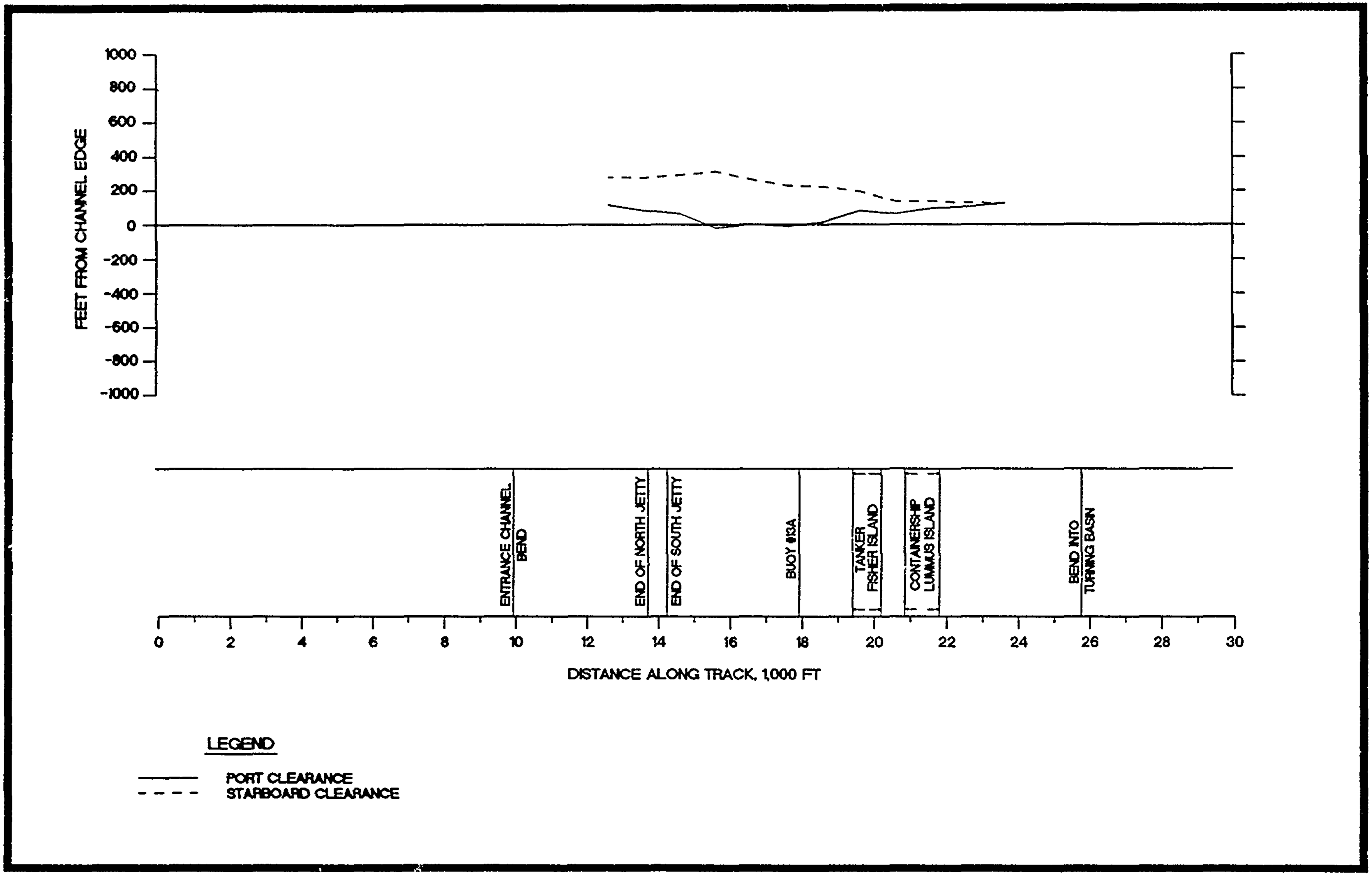


Figure 133. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, outbound, all runs

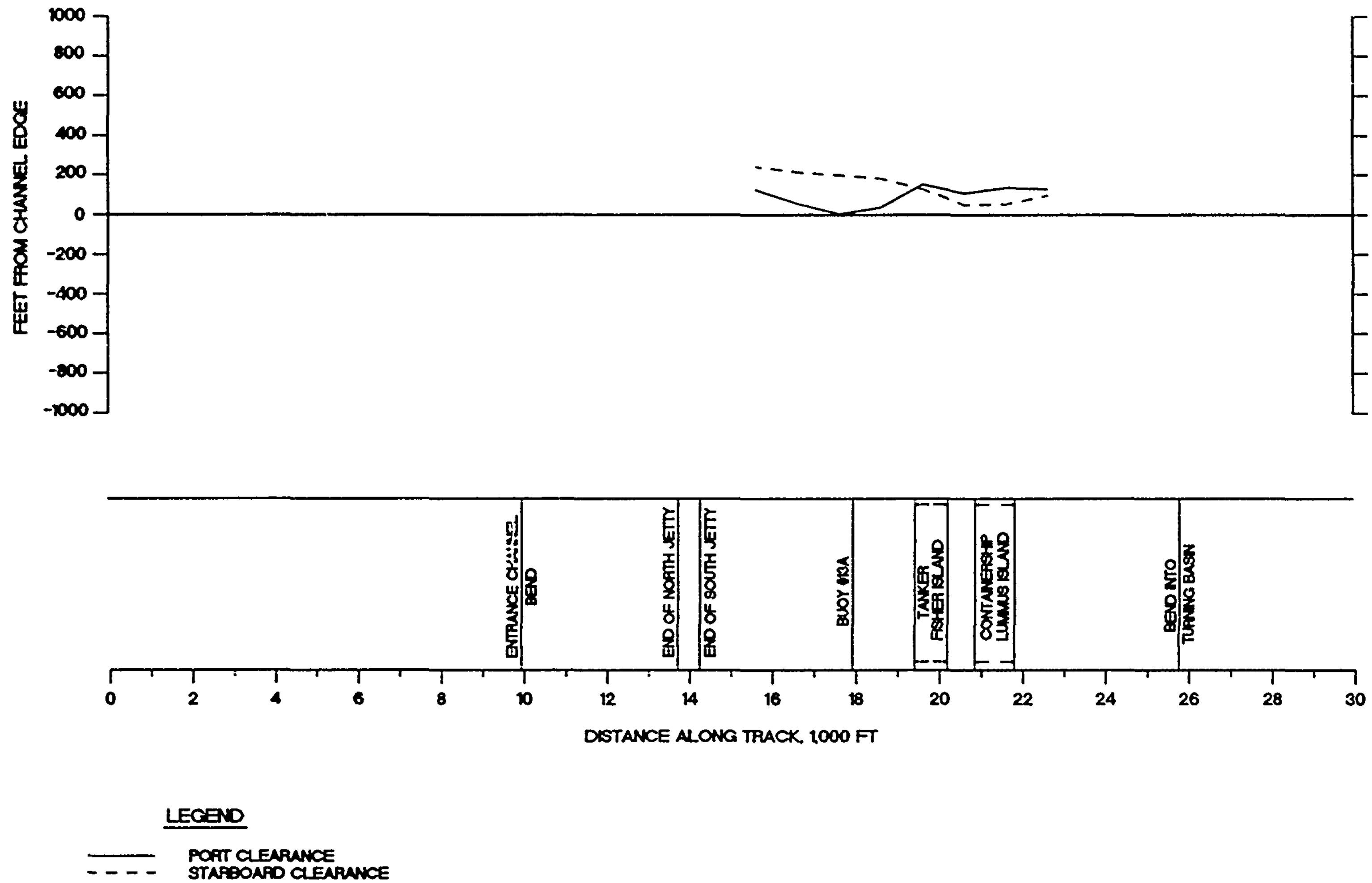


Figure 134. Port and starboard clearance, 1,000-ft channel sections, existing channel, 860-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

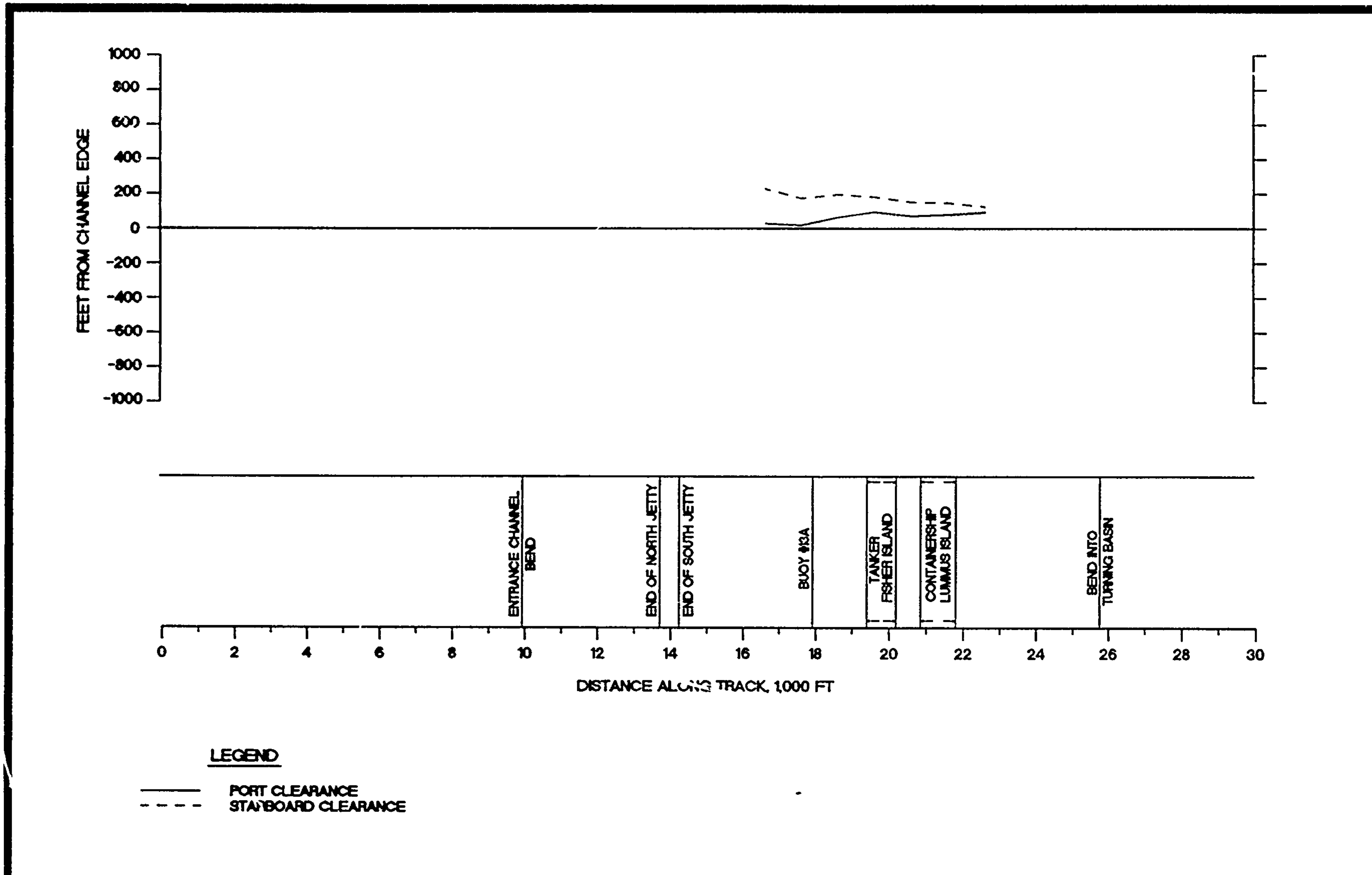


Figure 135. Port and starboard clearance, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, outbound, all runs

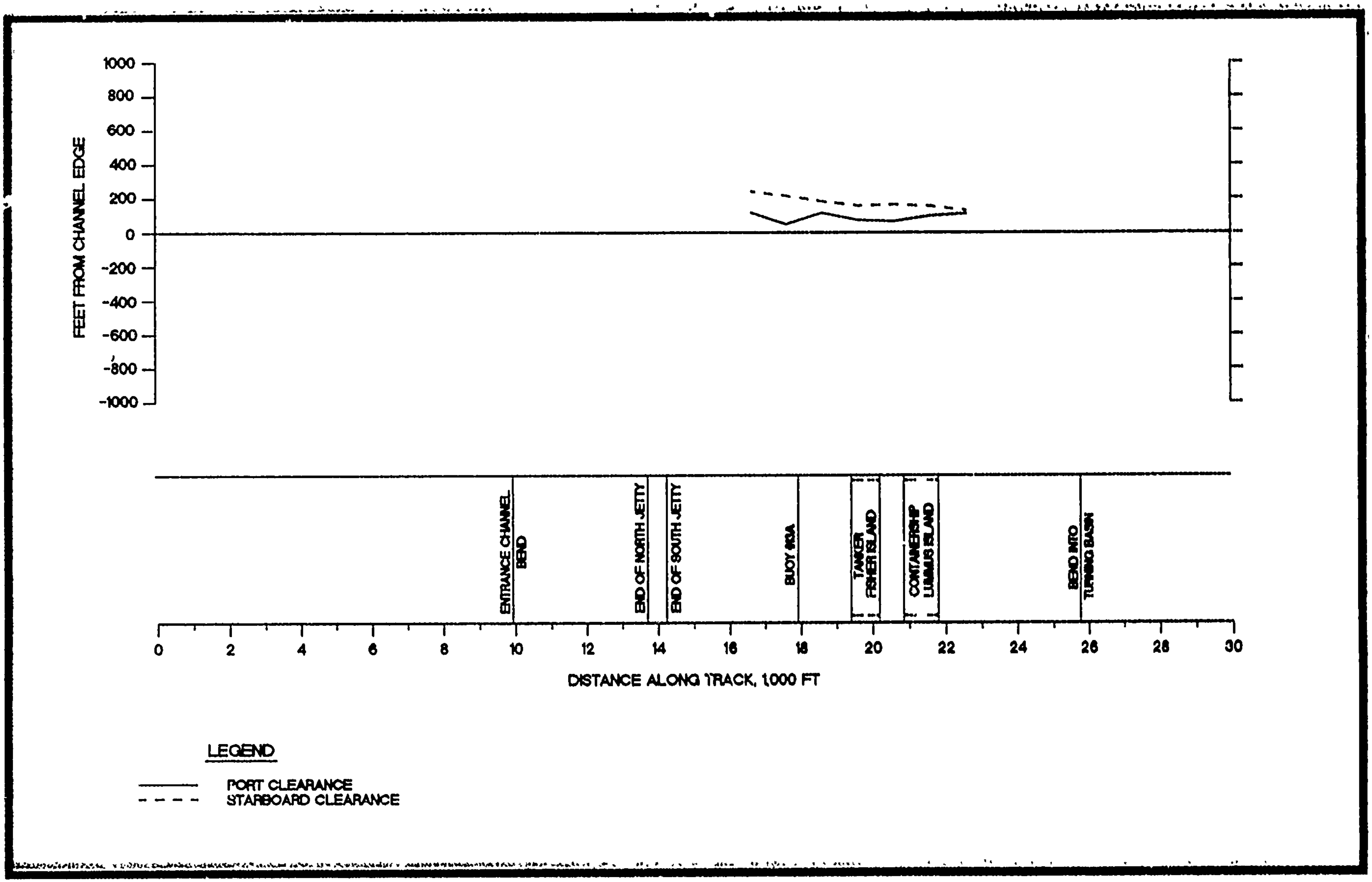


Figure 136. Port and starboard clearance, 1,000-ft channel sections, proposed channel, 950-ft containership, ebb tide, outbound, all runs

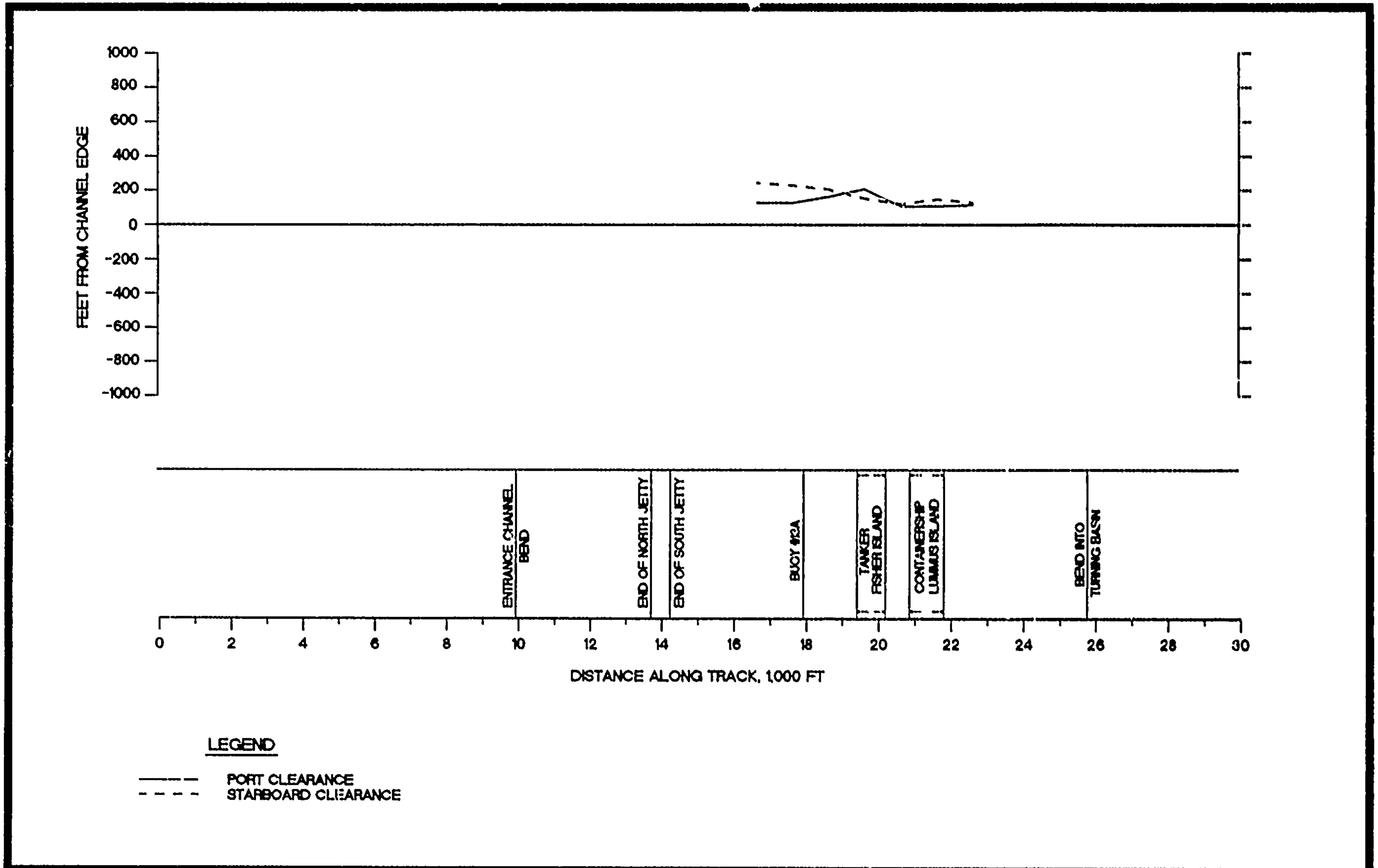


Figure 137. Port and starboard clearance, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, outbound, all runs

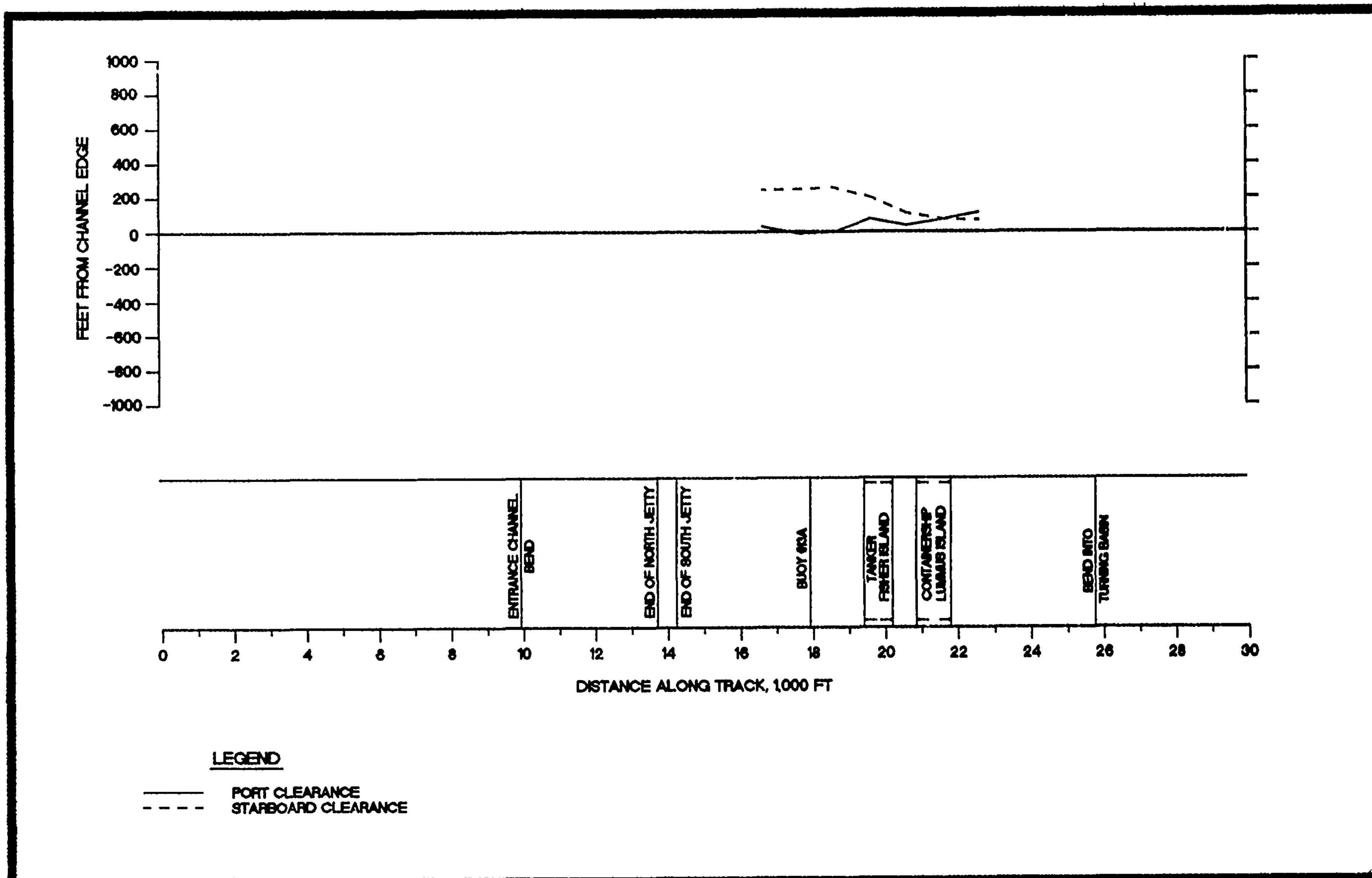


Figure 138. Port and starboard clearance, 1,000-ft channel sections, existing channel, 950-ft containership, ebb tide, with wind, outbound, all runs

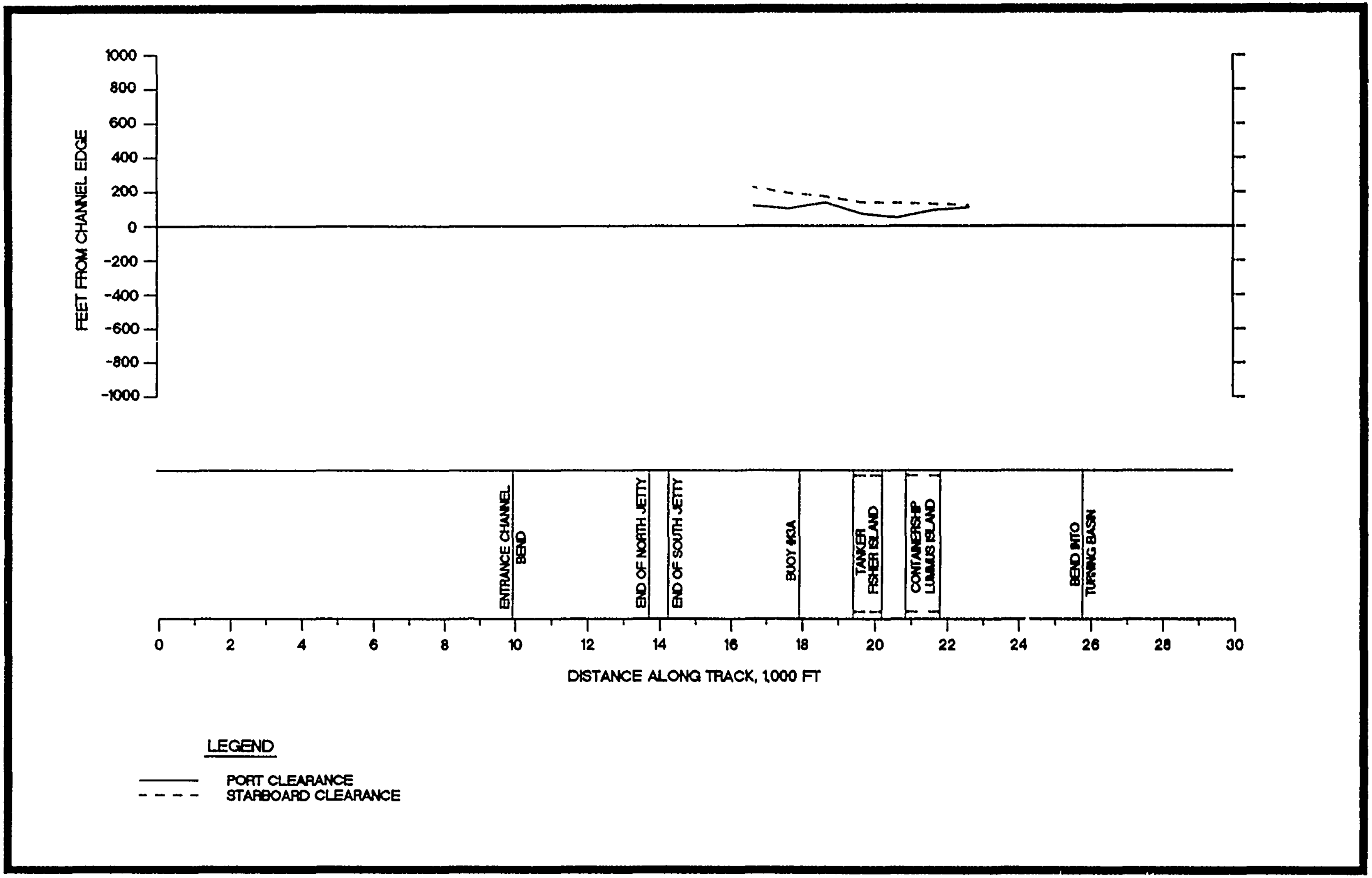


Figure 139. Port and starboard clearance, 1,0C0-ft channel sections, proposed channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

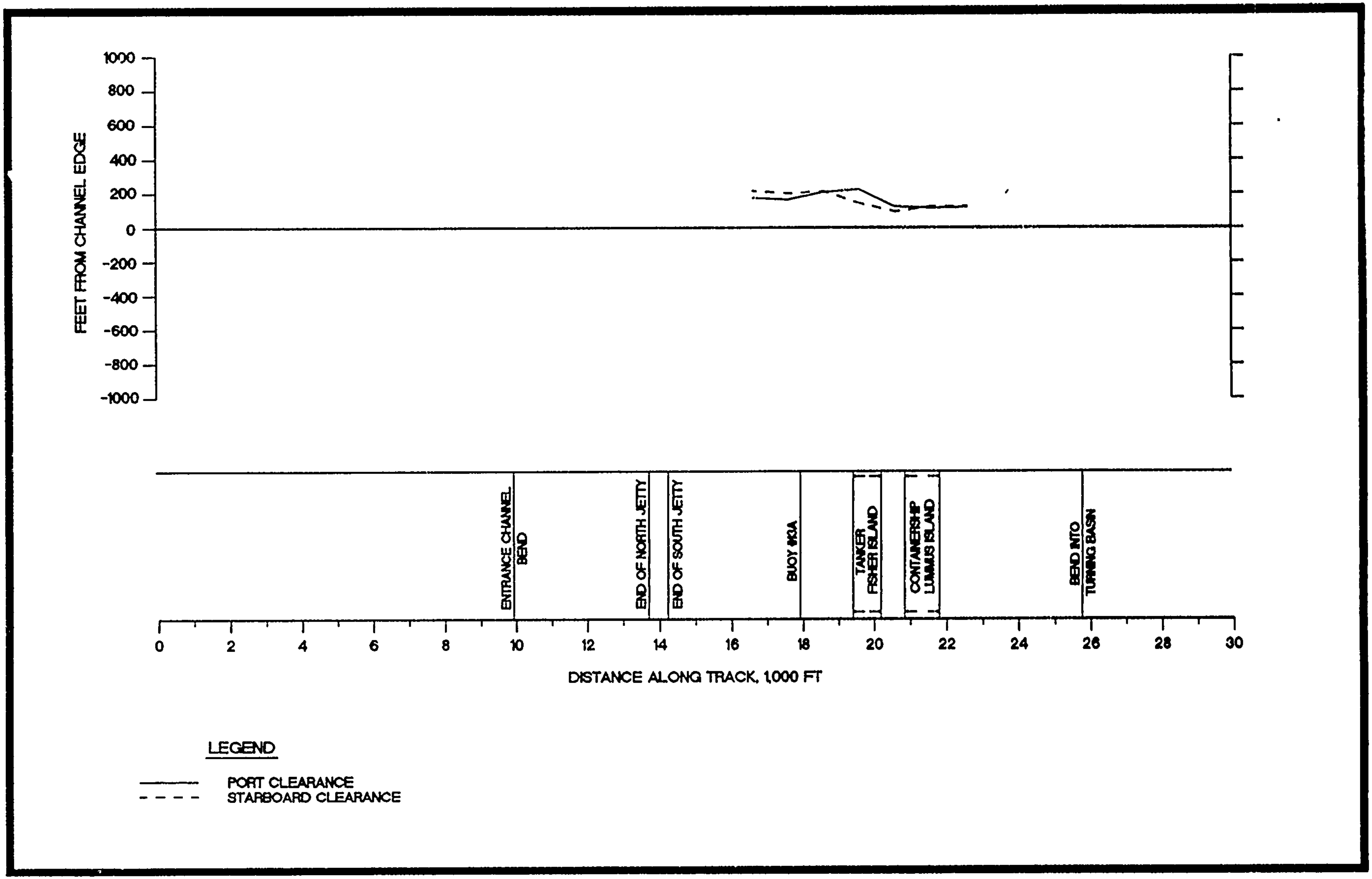


Figure 140. Port and starboard clearance, 1,000-ft channel sections, alternative channel, 950-ft containership, ebb tide, 25-knot northeast wind, outbound, all runs

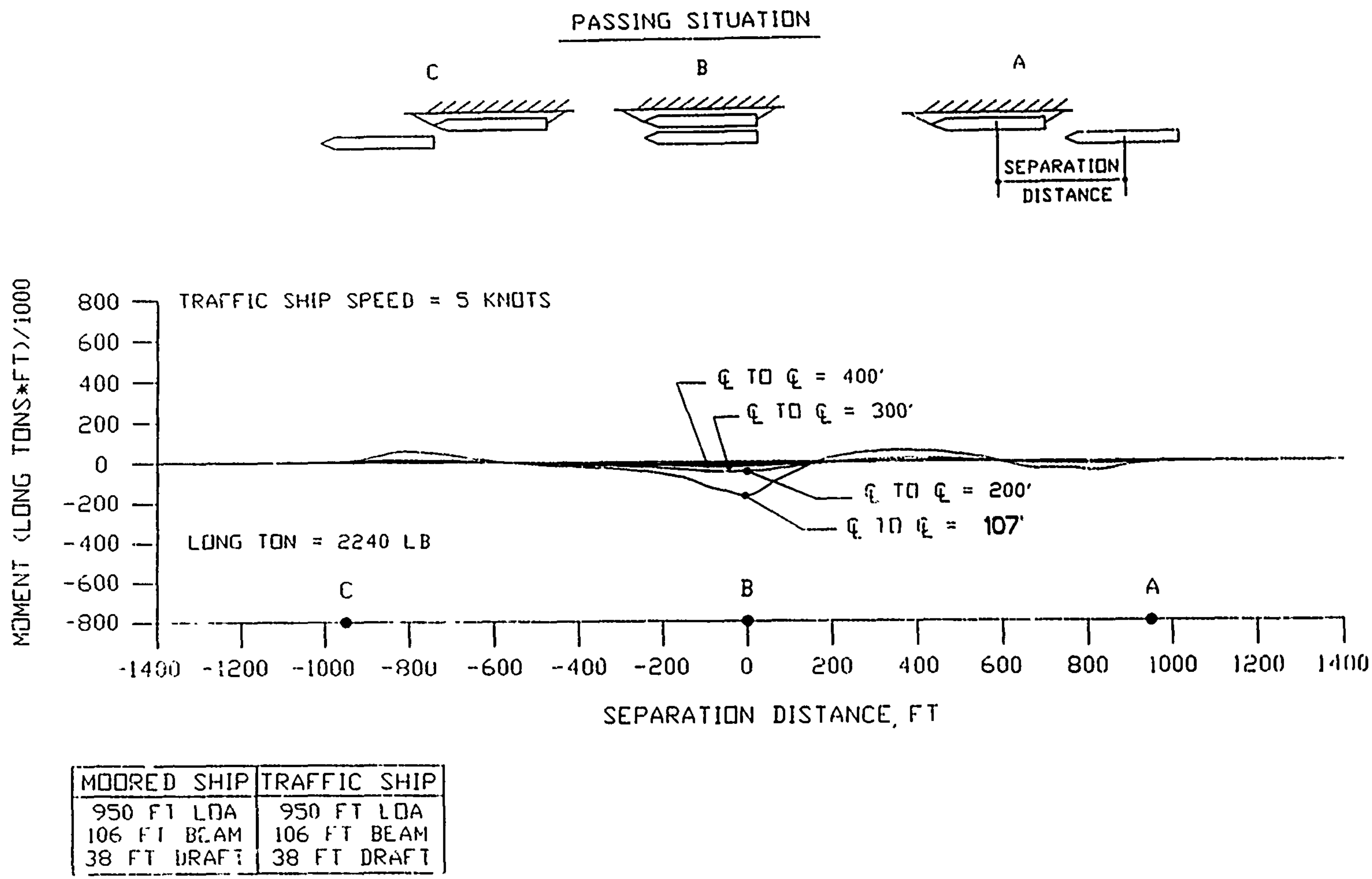
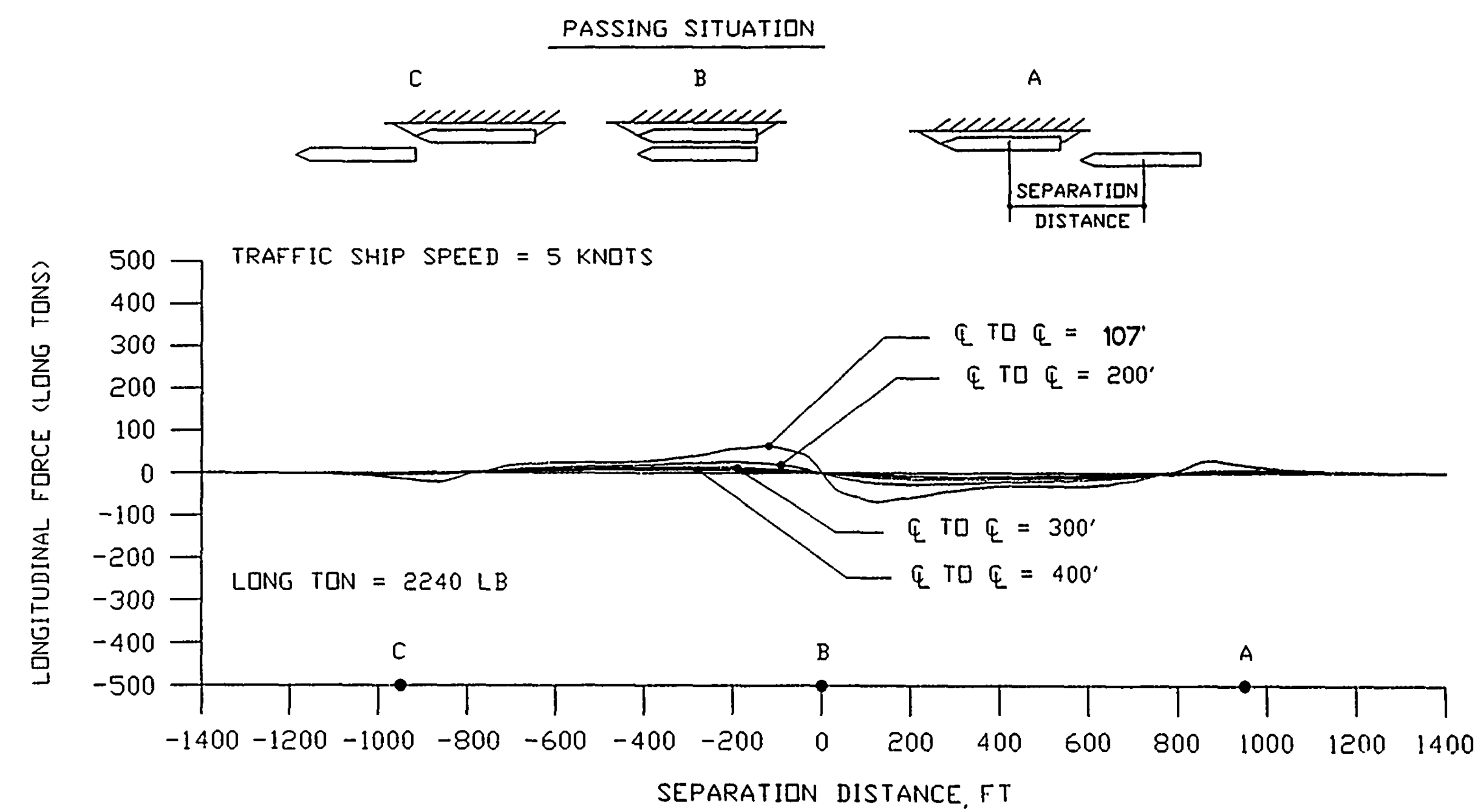


Figure 141. Ship/ship interaction, moment on moored ship, moored ship LOA 950 ft, traffic ship speed 5 knots, passing configuration



MOORED SHIP	TRAFFIC SHIP
950 FT LOA 106 FT BEAM 38 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 142. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 950 ft, traffic ship speed 5 knots, passing configuration

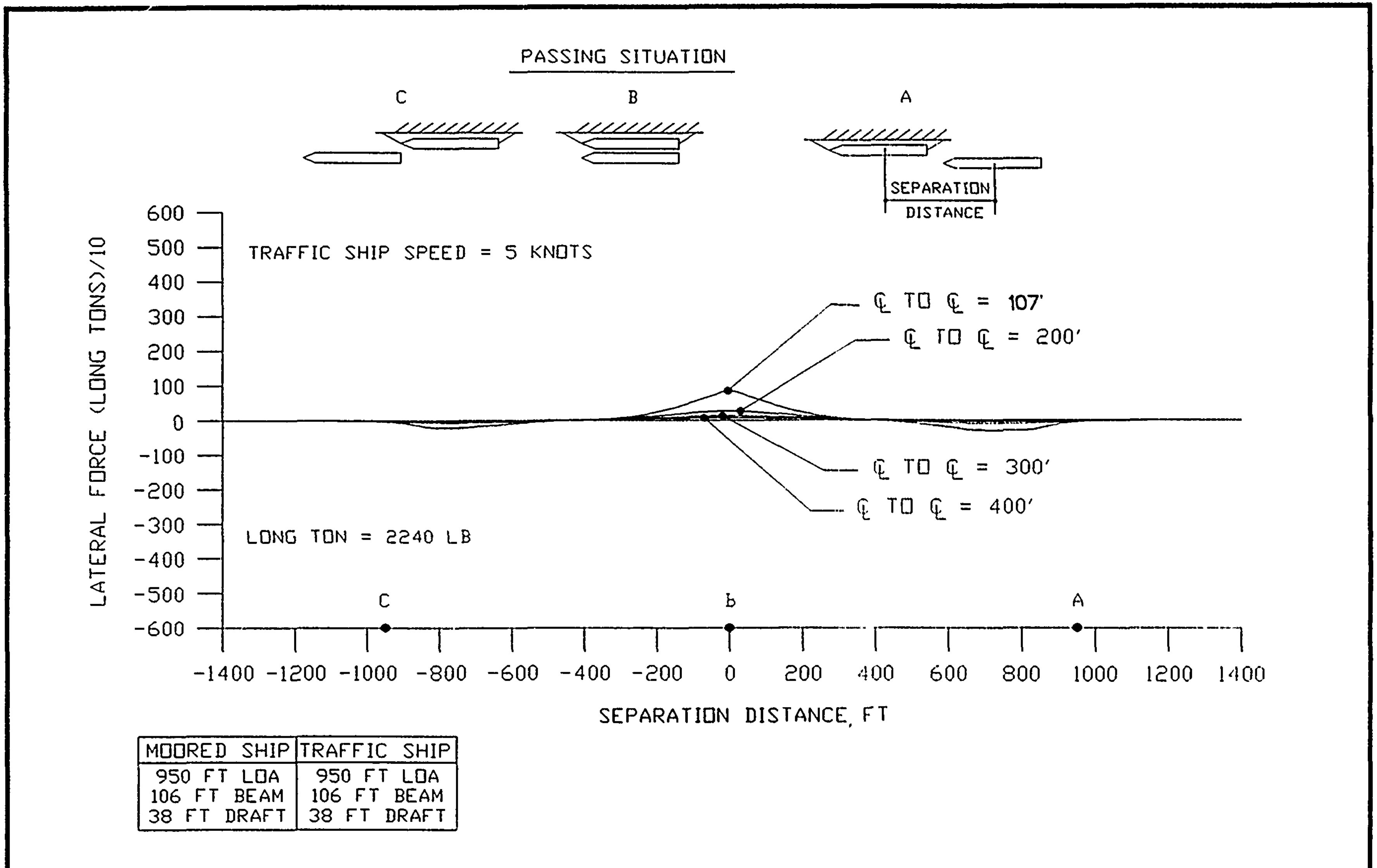
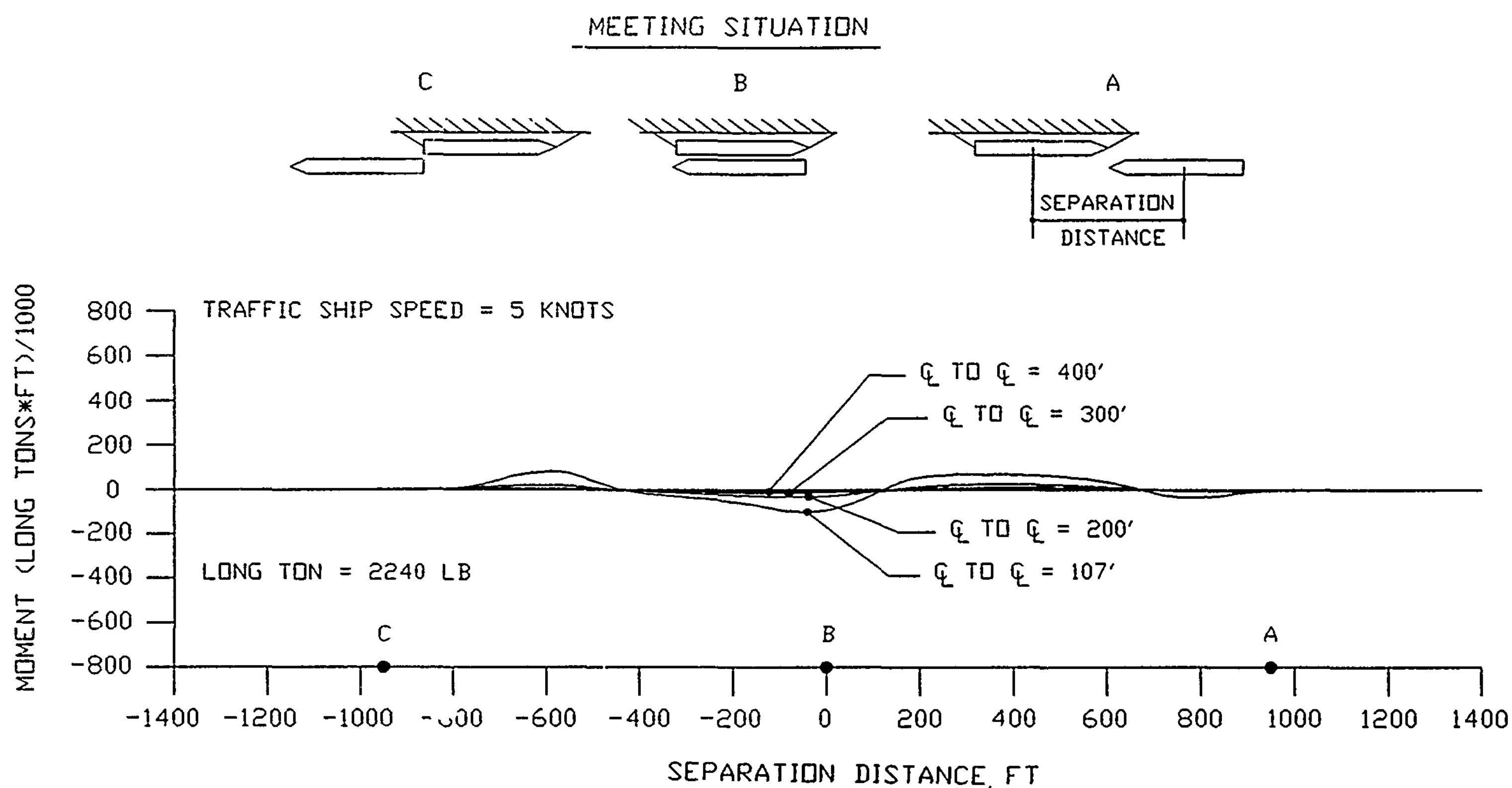
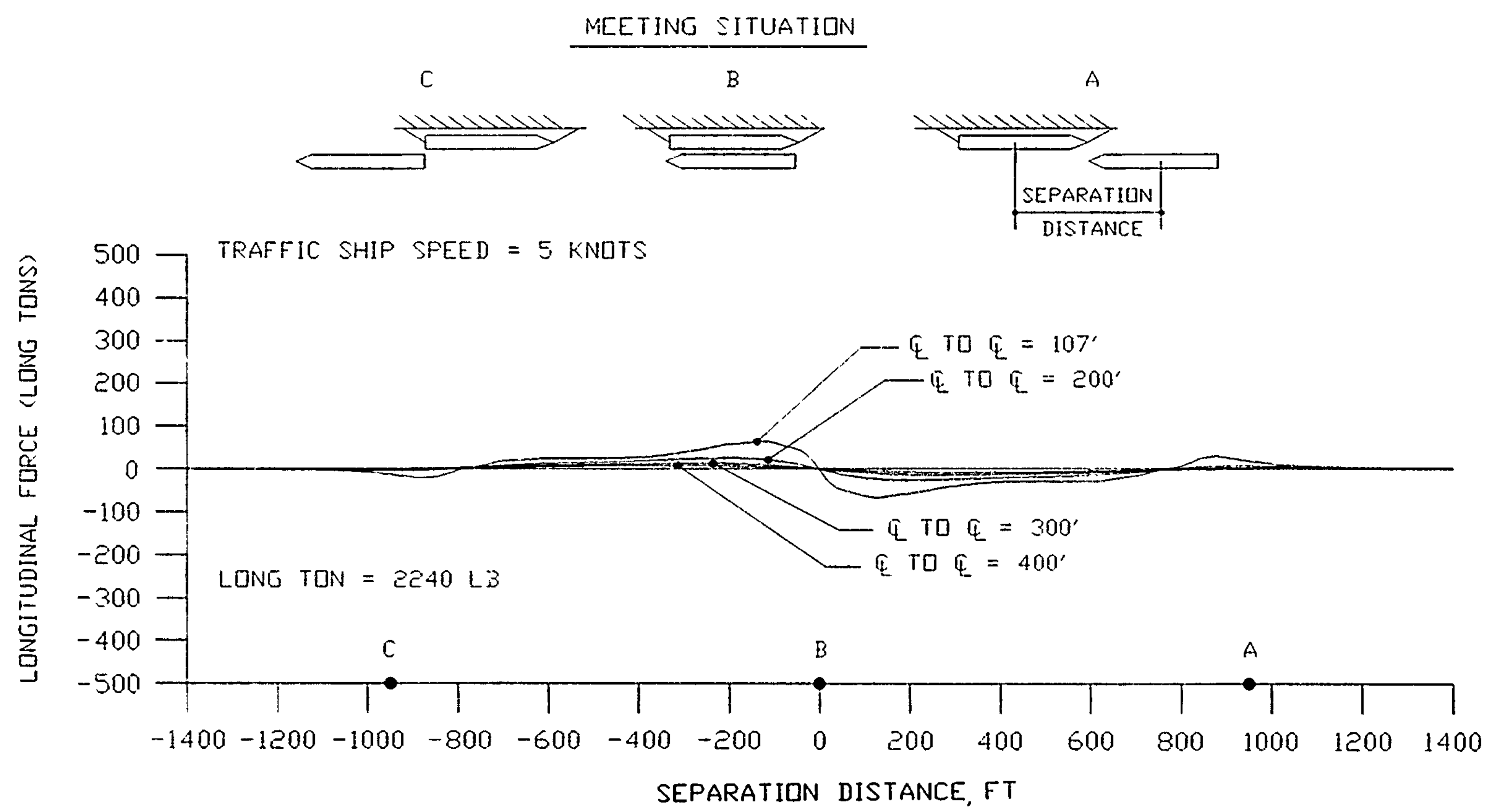


Figure 143. Ship/ship interaction, lateral force on moored ship, moored ship LOA 950 ft, traffic ship speed 5 knots, passing configuration



MOORED SHIP	TRAFFIC SHIP
950 FT LOA 106 FT BEAM 38 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 144. Ship/ship interaction, moment on moored ship, moored ship LOA 950 ft, traffic ship speed 5 knots, meeting configuration



MOORED SHIP	TRAFFIC SHIP
950 FT LOA 106 FT BEAM 38 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 145. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 950 ft, traffic ship speed 5 knots, meeting configuration

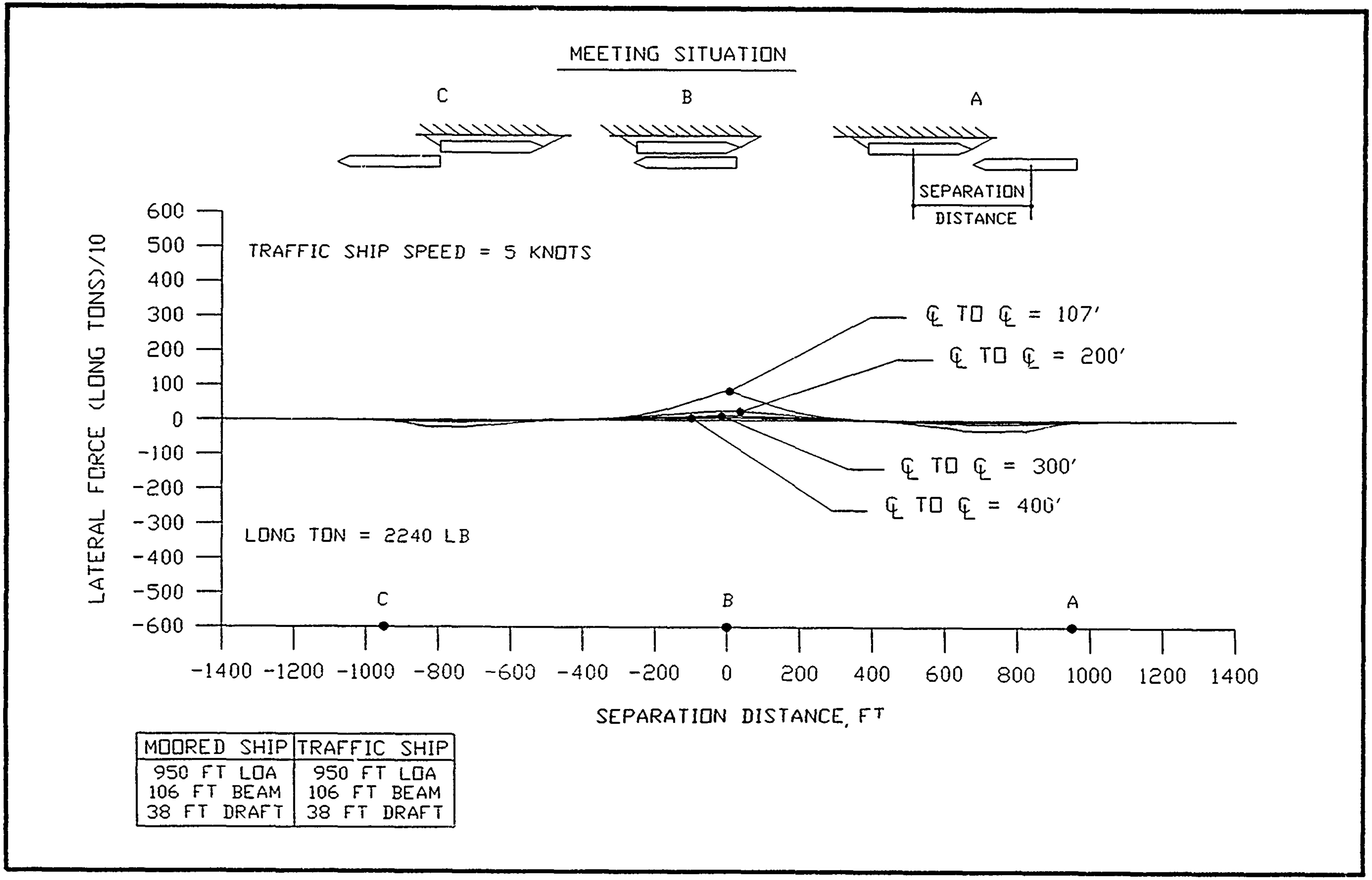
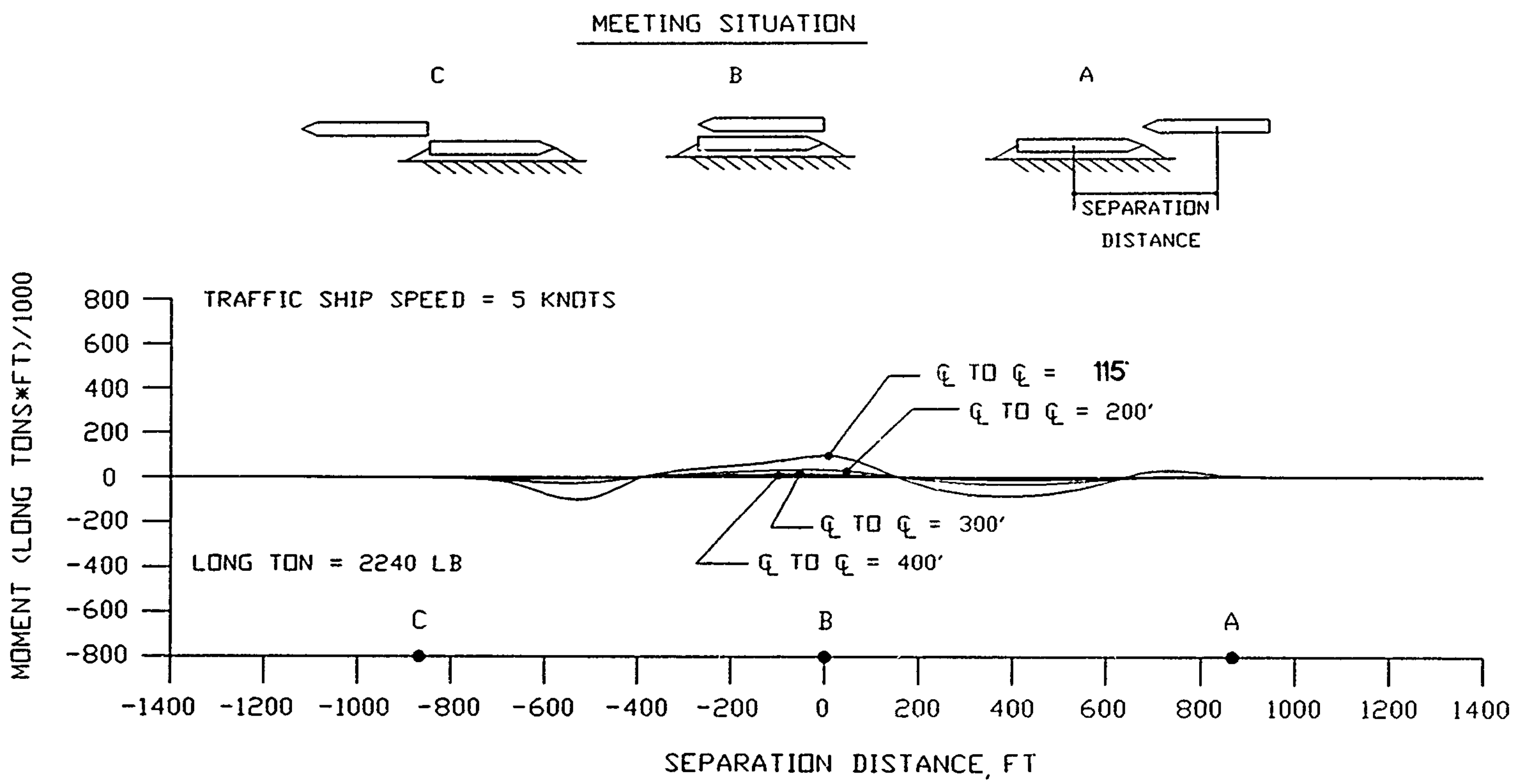


Figure 146. Ship/ship interaction, lateral force on moored ship, moored ship LOA 950 ft, traffic ship speed 5 knots, meeting configuration



MOORED SHIP	TRAFFIC SHIP
784 FT LOA 122 FT BEAM 40 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 147. Ship/ship interaction, moment on moored ship, moored ship LOA 784 ft, traffic ship speed 5 knots, meeting configuration

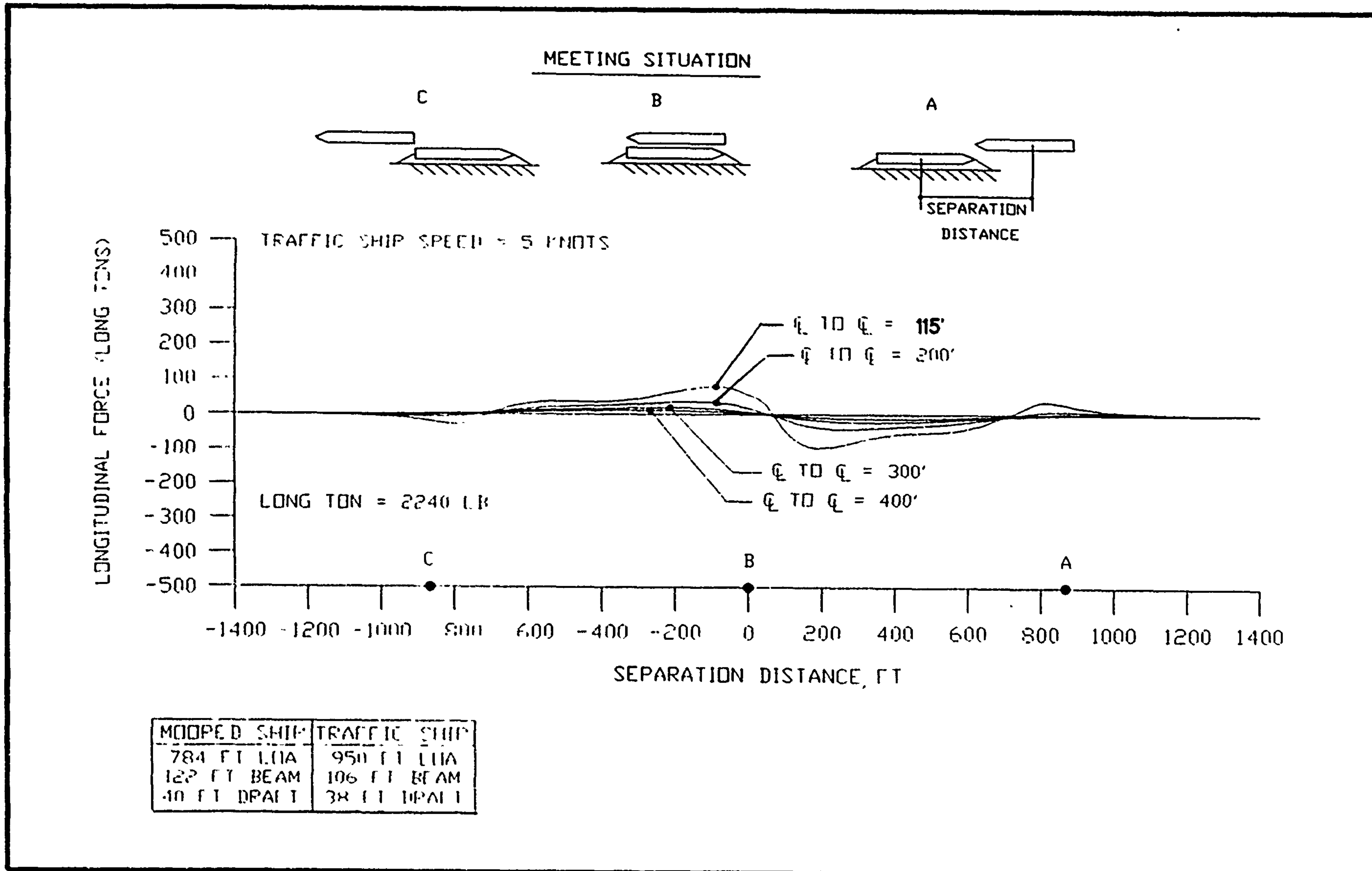
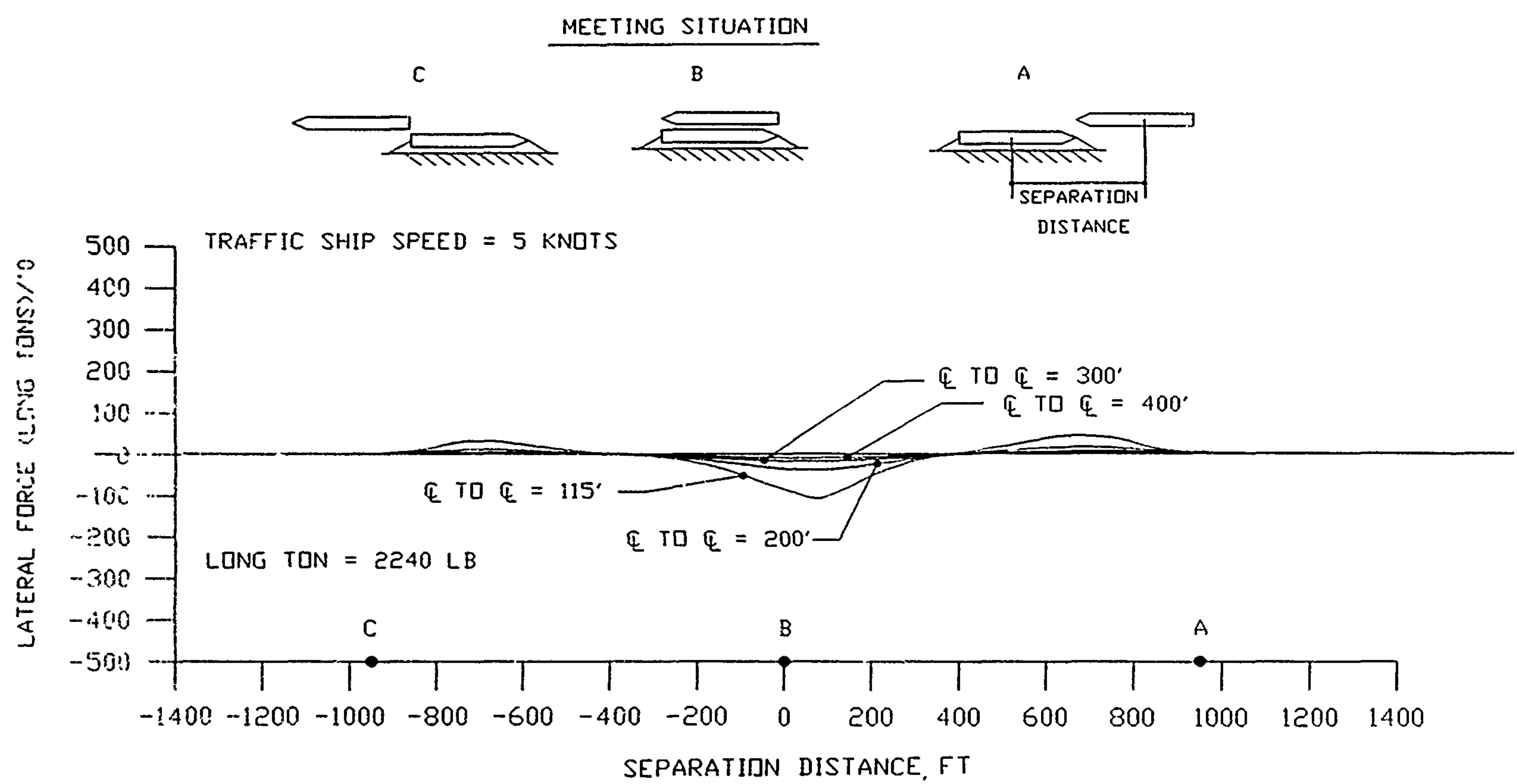
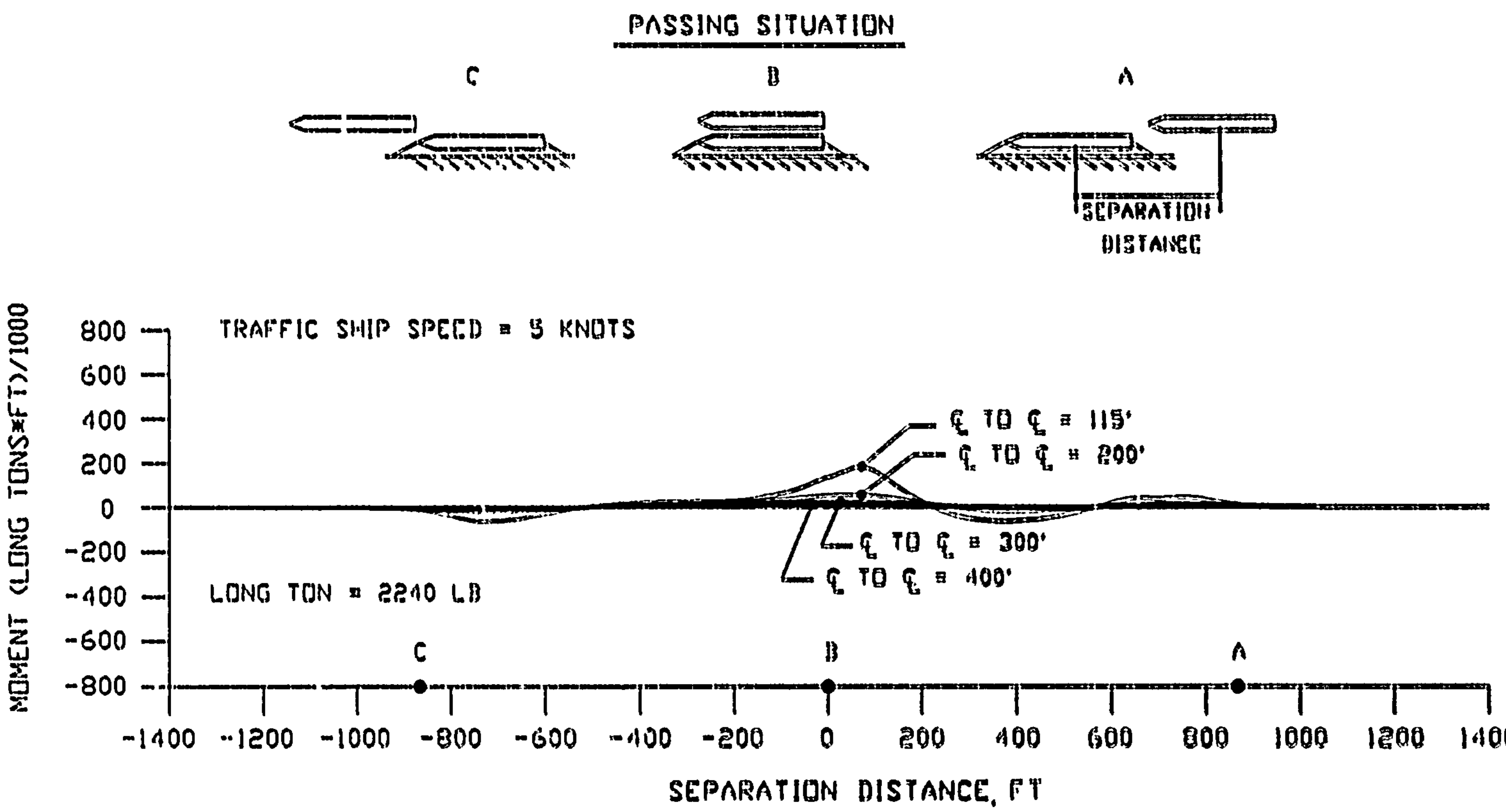


Figure 148. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 784 ft, traffic ship speed 5 knots, meeting configuration



MOORED SHIP	TRAFFIC SHIP
784 FT LOA	950 FT LOA
122 FT BEAM	106 FT BEAM
40 FT DRAFT	38 FT DRAFT

Figure 149. Ship/ship interaction, lateral force on moored ship, moored ship LOA 784 ft, traffic ship speed 5 knots, meeting configuration



MOORED SHIP	TRAFFIC SHIP
784 FT LOA 122 FT BEAM 40 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 150. Ship/ship interaction, moment on moored ship, moored ship LOA 784 ft, traffic ship speed 5 knots, passing configuration

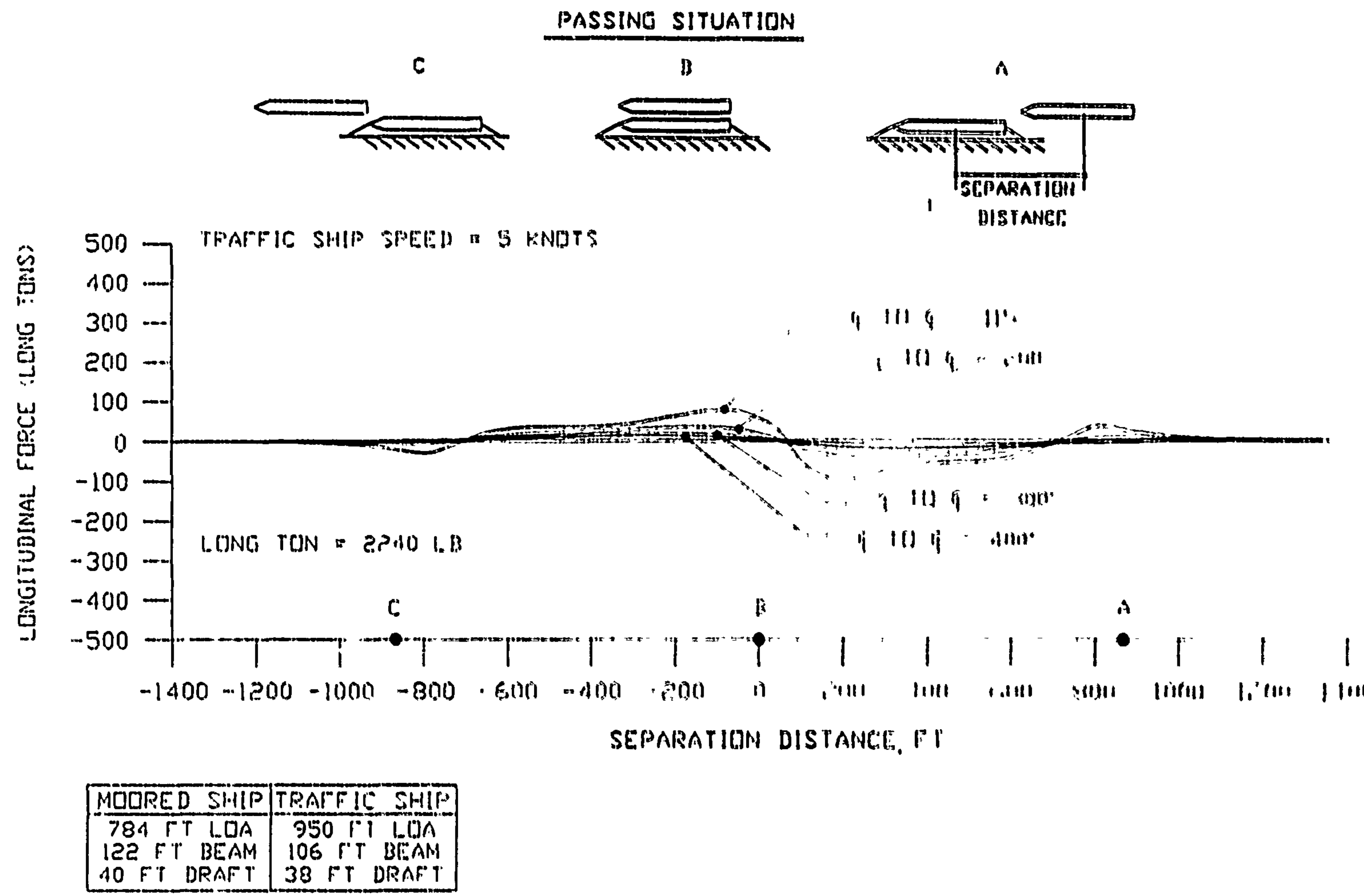


Figure 151. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 784 ft, traffic ship speed 5 knots, passing configuration

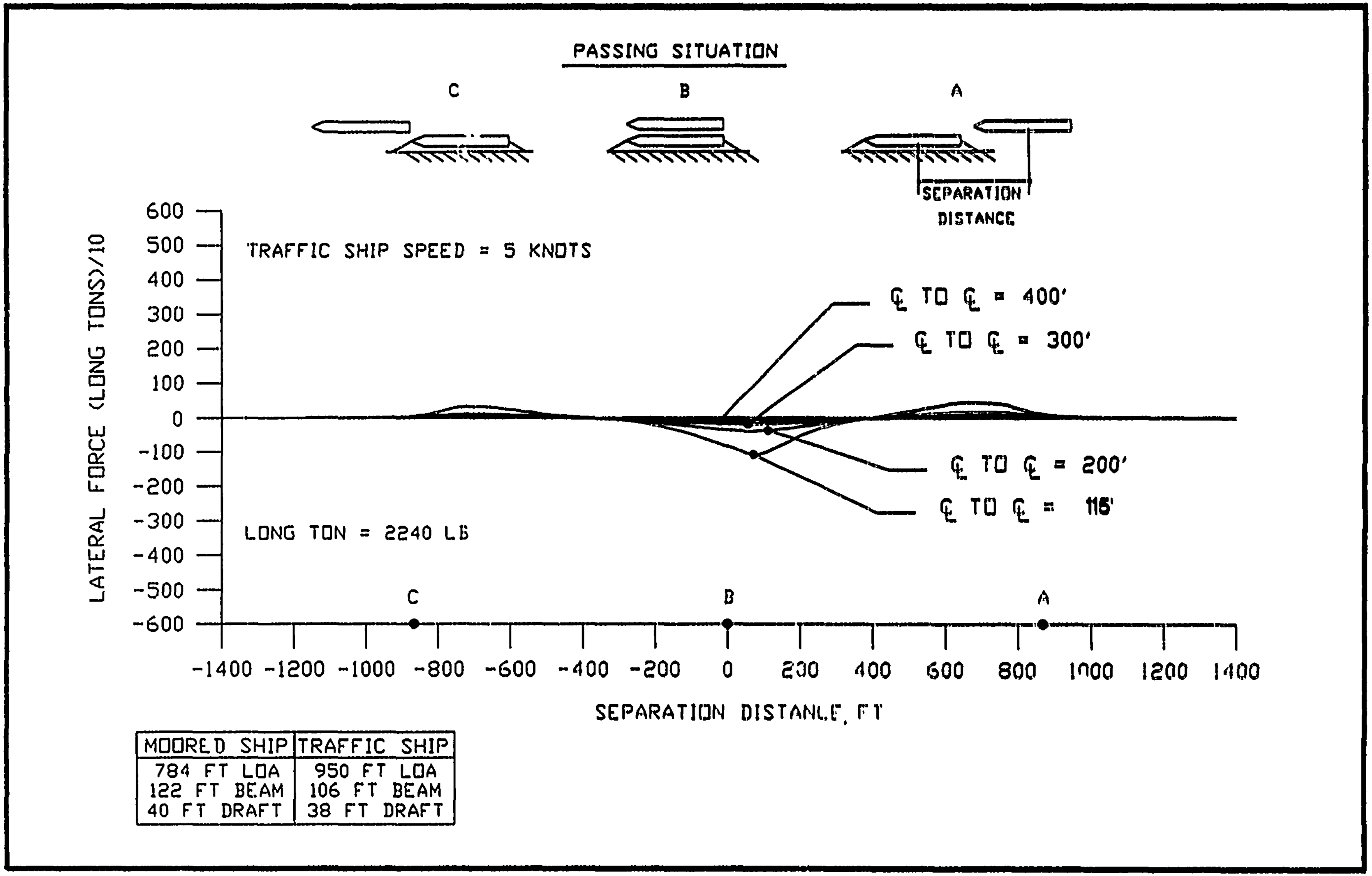


Figure 152. Ship/ship interaction, lateral force on moored ship, moored ship LOA 784 ft, traffic ship speed 5 knots, passing configuration

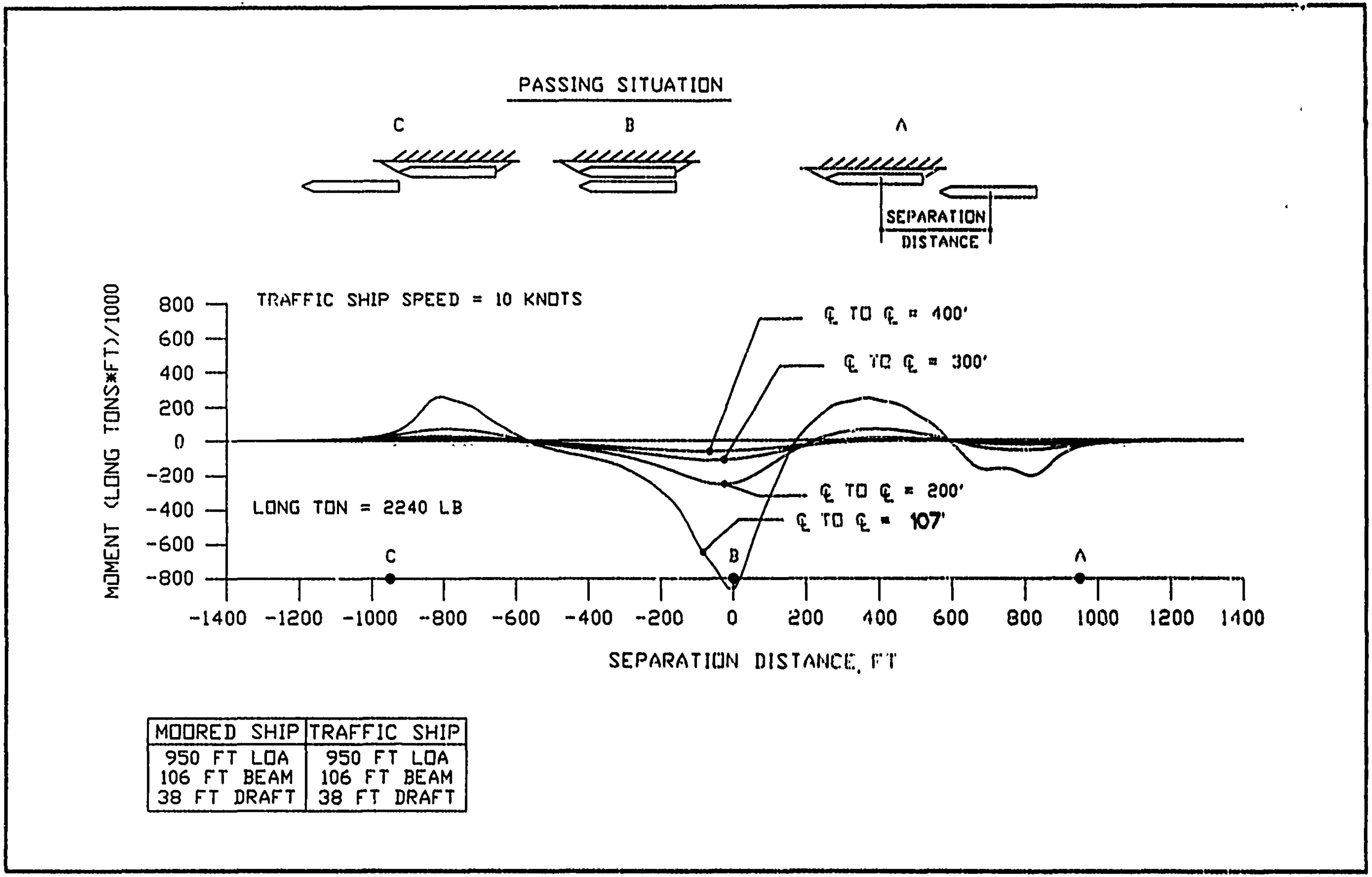
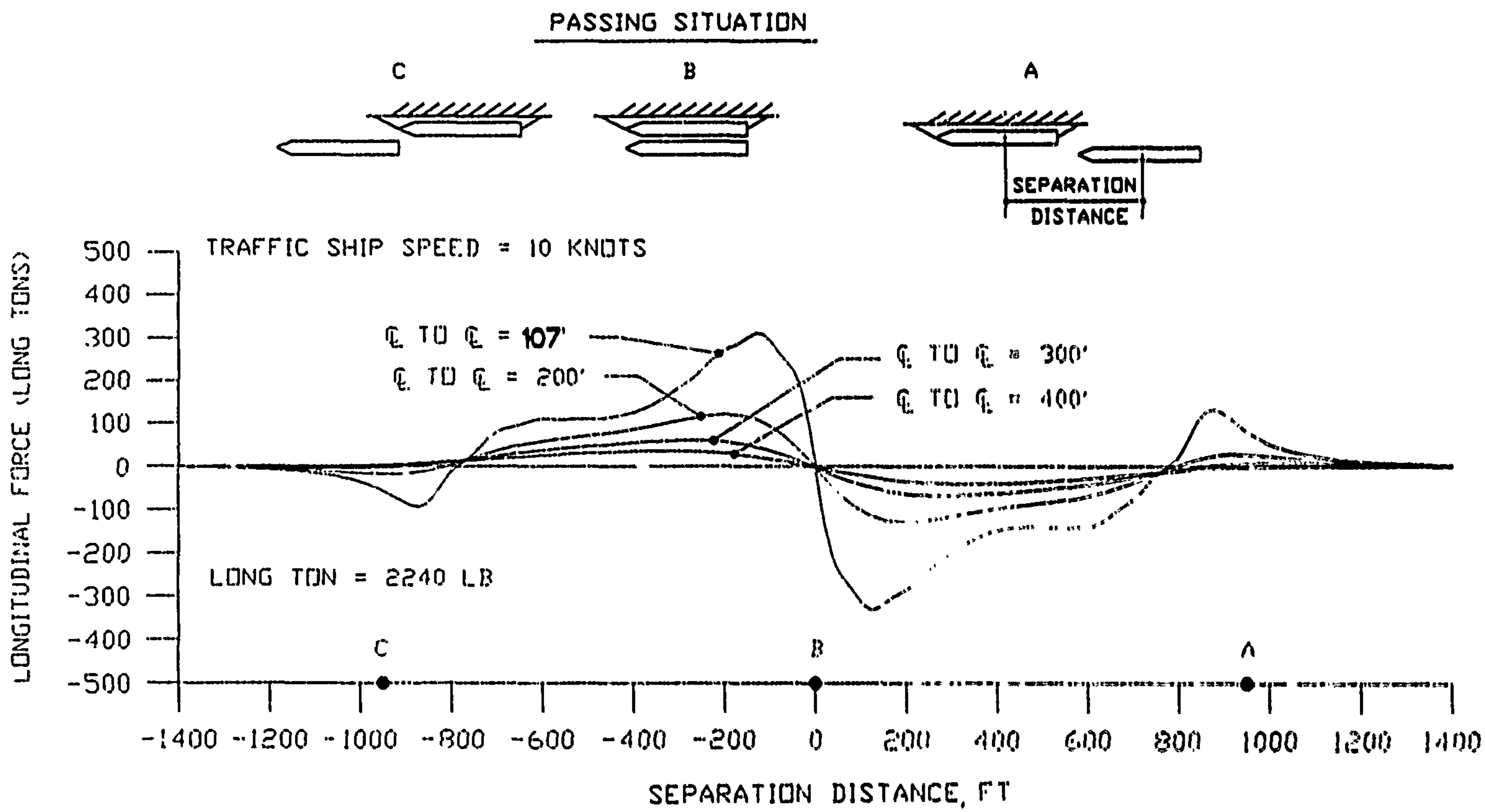


Figure 153. Ship/ship interaction, moment on moored ship, moored ship LOA 950 ft, traffic ship speed 10 knots, passing configuration



MOORED SHIP	TRAFFIC SHIP
950 FT LOA	950 FT LOA
106 FT BEAM	106 FT BEAM
38 FT DRAFT	38 FT DRAFT

Figure 154. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 950 ft, traffic ship speed 10 knots, passing configuration

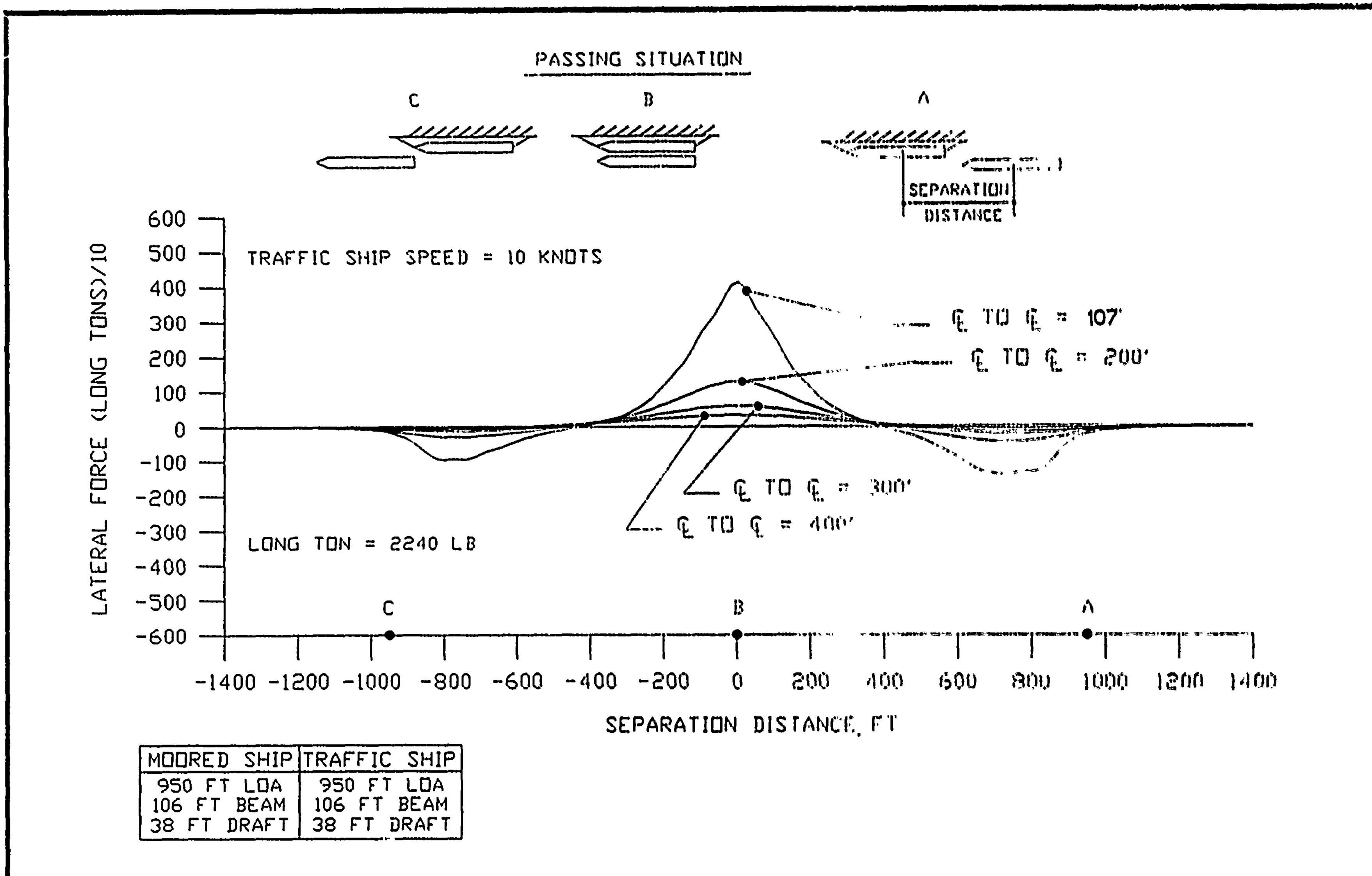
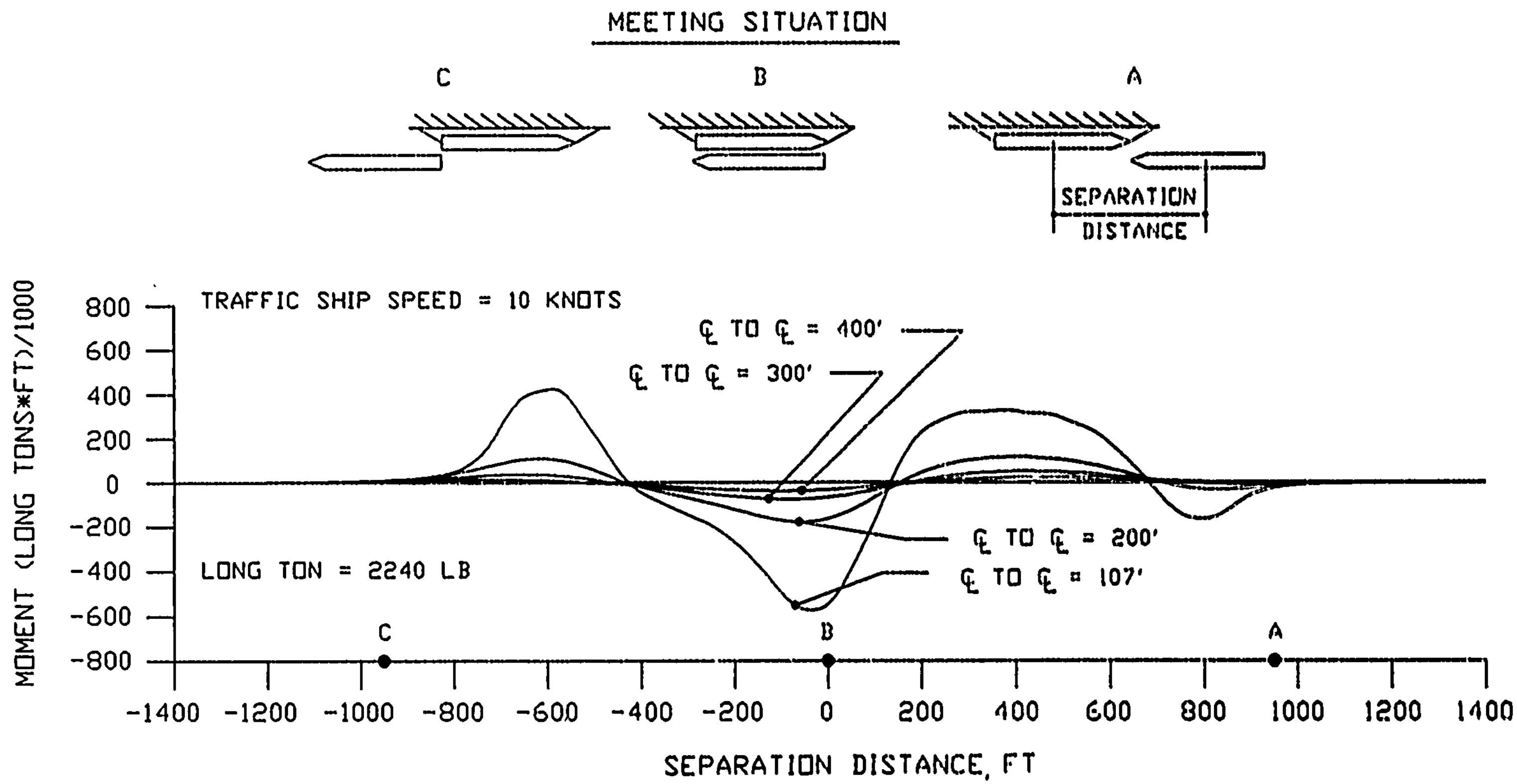


Figure 155. Ship/ship interaction, lateral force on moored ship, moored ship LOA 950 ft, traffic ship speed 10 knots, passing configuration.



MOORED SHIP	TRAFFIC SHIP
950 FT LOA 106 FT BEAM 38 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 156. Ship/ship interaction, moment on moored ship, moored ship LOA 950 ft, traffic ship speed 10 knots, meeting configuration

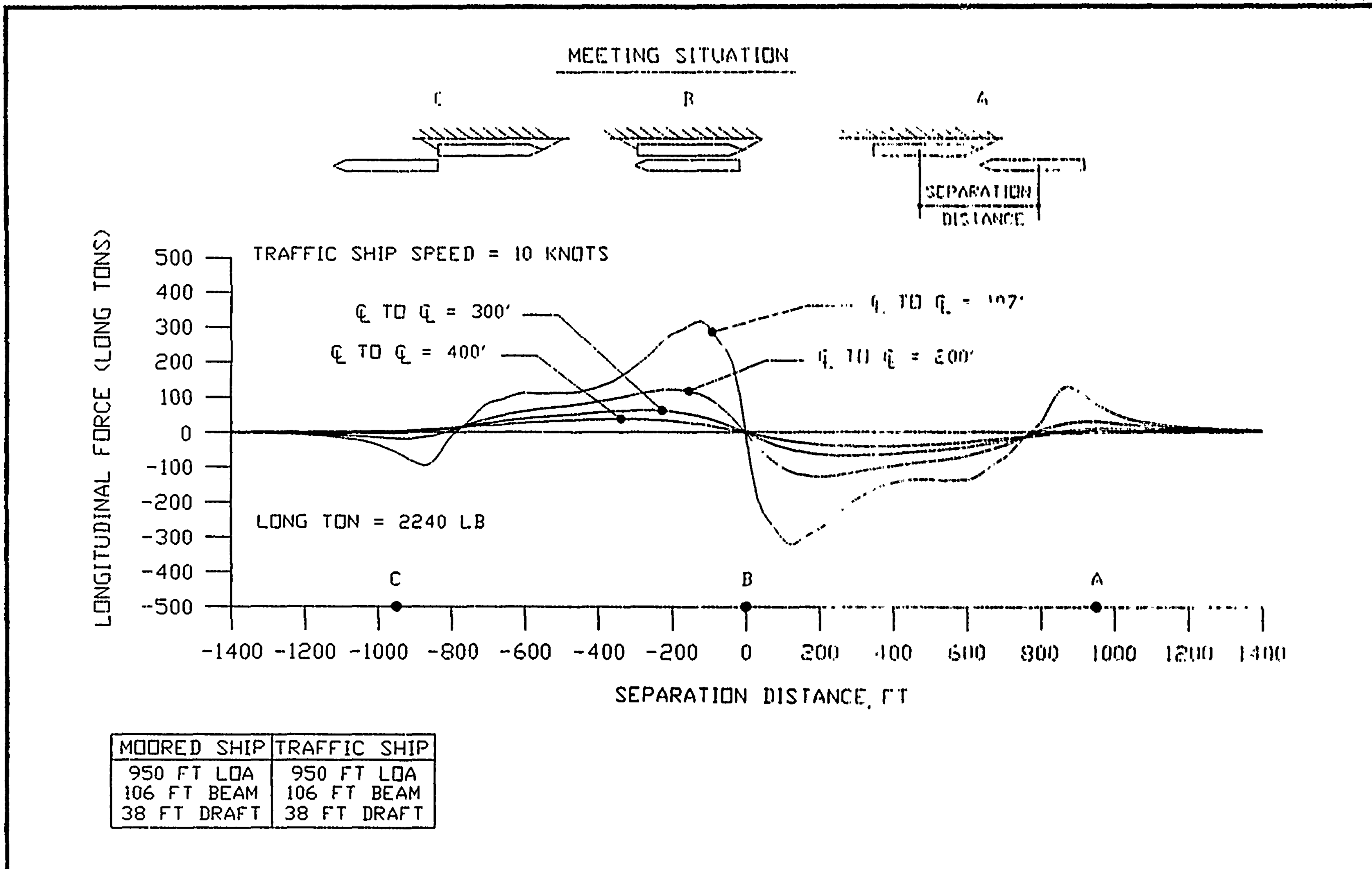


Figure 157. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 950 ft, traffic ship speed 10 knots, meeting configuration

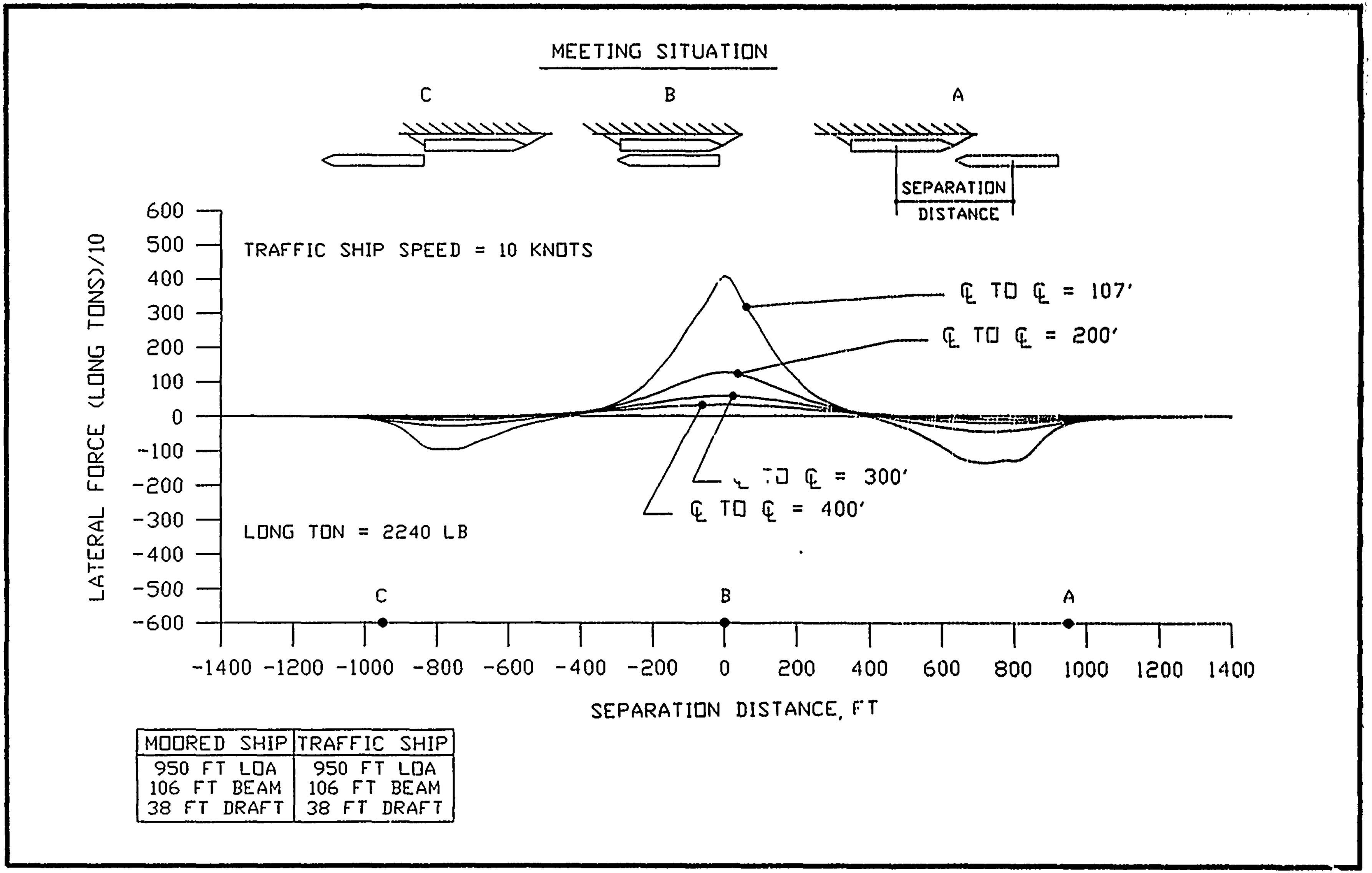
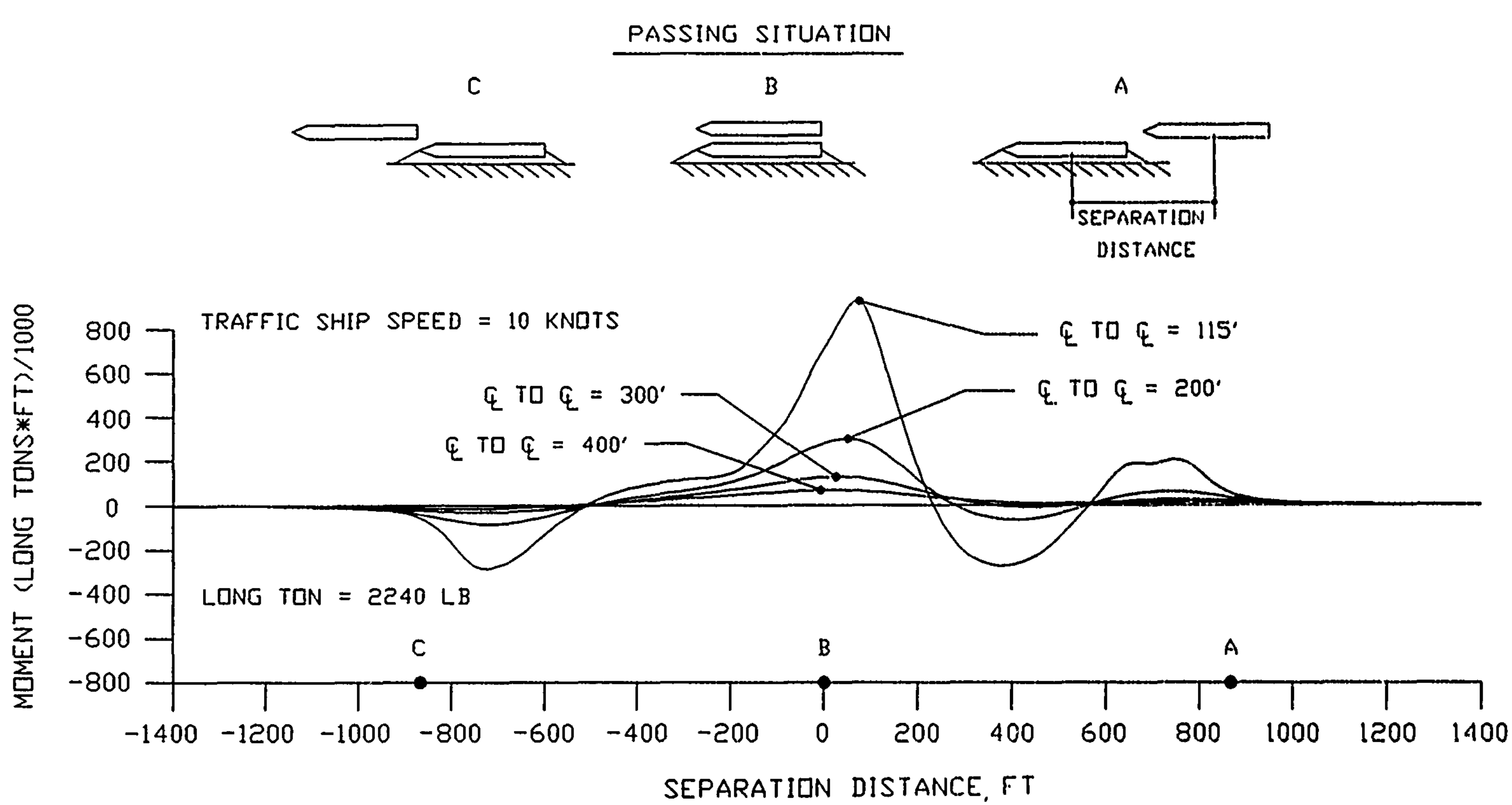
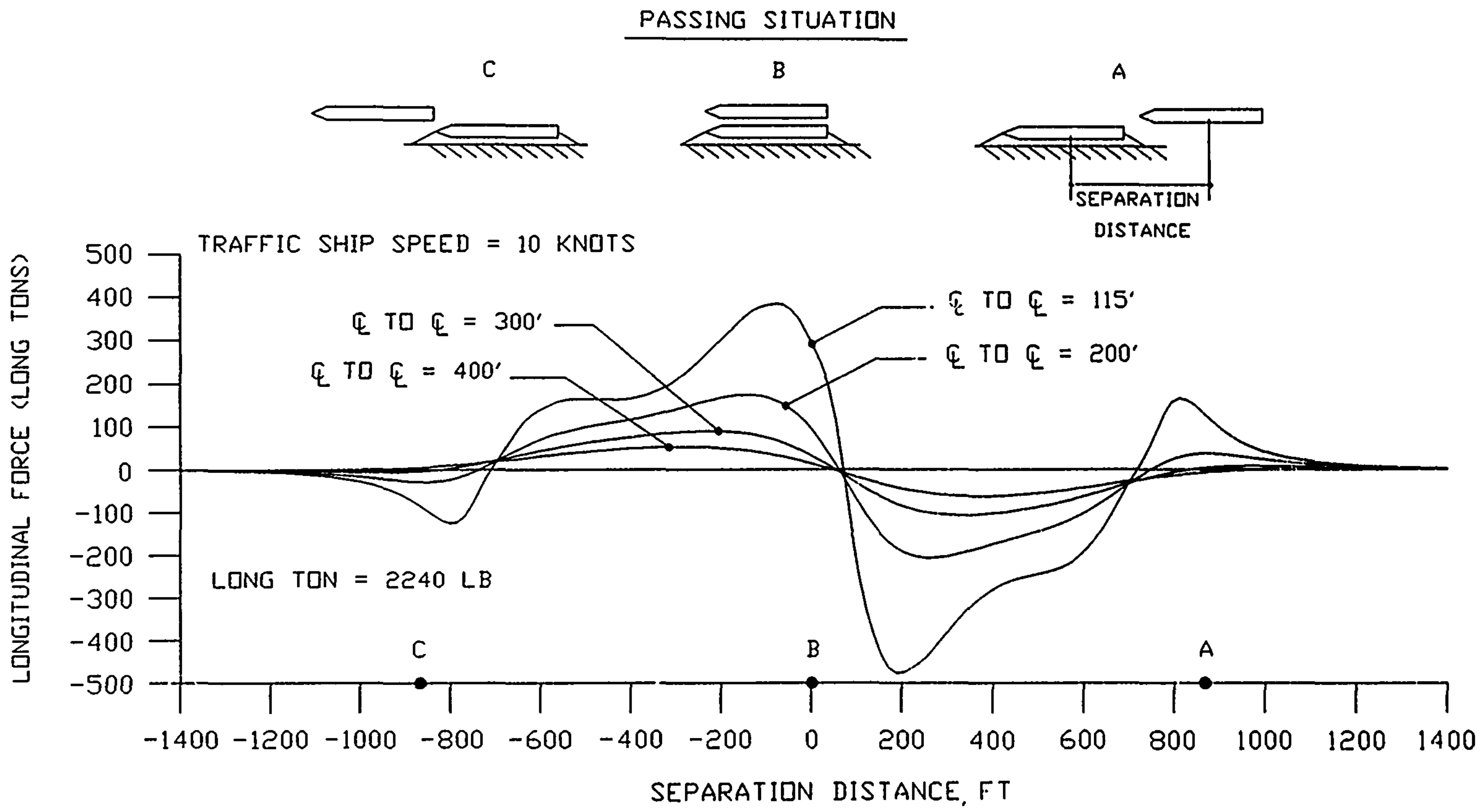


Figure 158. Ship/ship interaction, lateral force on moored ship, moored ship LOA 950 ft, traffic ship speed 10 knots, meeting configuration



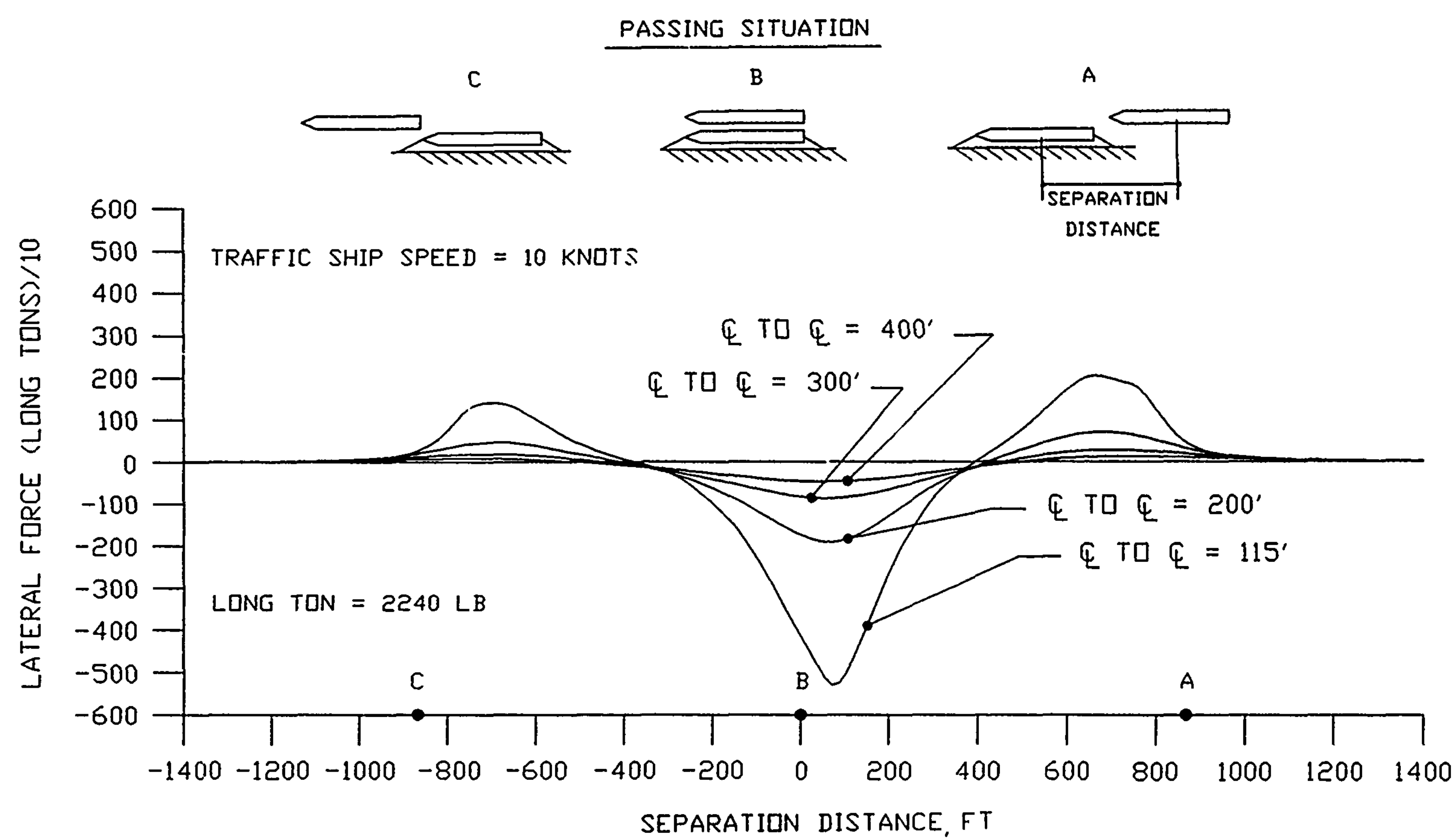
MOORED SHIP	TRAFFIC SHIP
784 FT LOA 122 FT BEAM 40 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 159. Ship/ship interaction, moment on moored ship, moored ship LOA 784 ft, traffic ship speed 10 knots, passing configuration



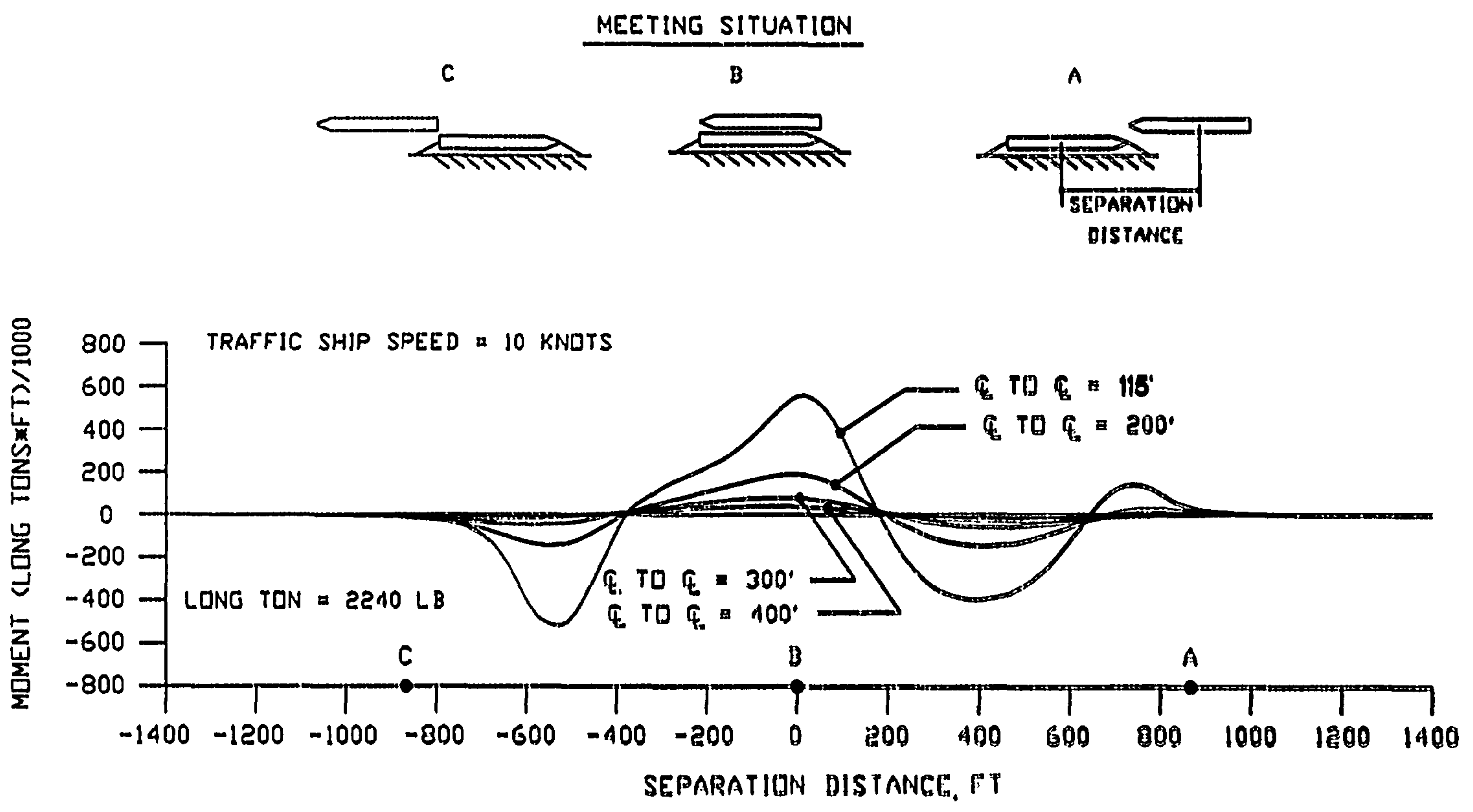
MOORED SHIP	TRAFFIC SHIP
784 FT LOA	950 FT LOA
122 FT BEAM	106 FT BEAM
40 FT DRAFT	38 FT DRAFT

Figure 160. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 784 ft, traffic ship speed 10 knots, passing configuration



MOORED SHIP	TRAFFIC SHIP
784 FT LOA 122 FT BEAM 40 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 161. Ship/ship interaction, lateral force on moored ship, moored ship LOA 784 ft, traffic ship speed 10 knots, passing configuration



MOORED SHIP	TRAFFIC SHIP
784 FT LOA	950 FT LOA
122 FT BEAM	106 FT BEAM
40 FT DRAFT	38 FT DRAFT

Figure 162. Ship/ship interaction, moment on moored ship, moored ship LOA 784 ft, traffic ship speed 10 knots, meeting configuration

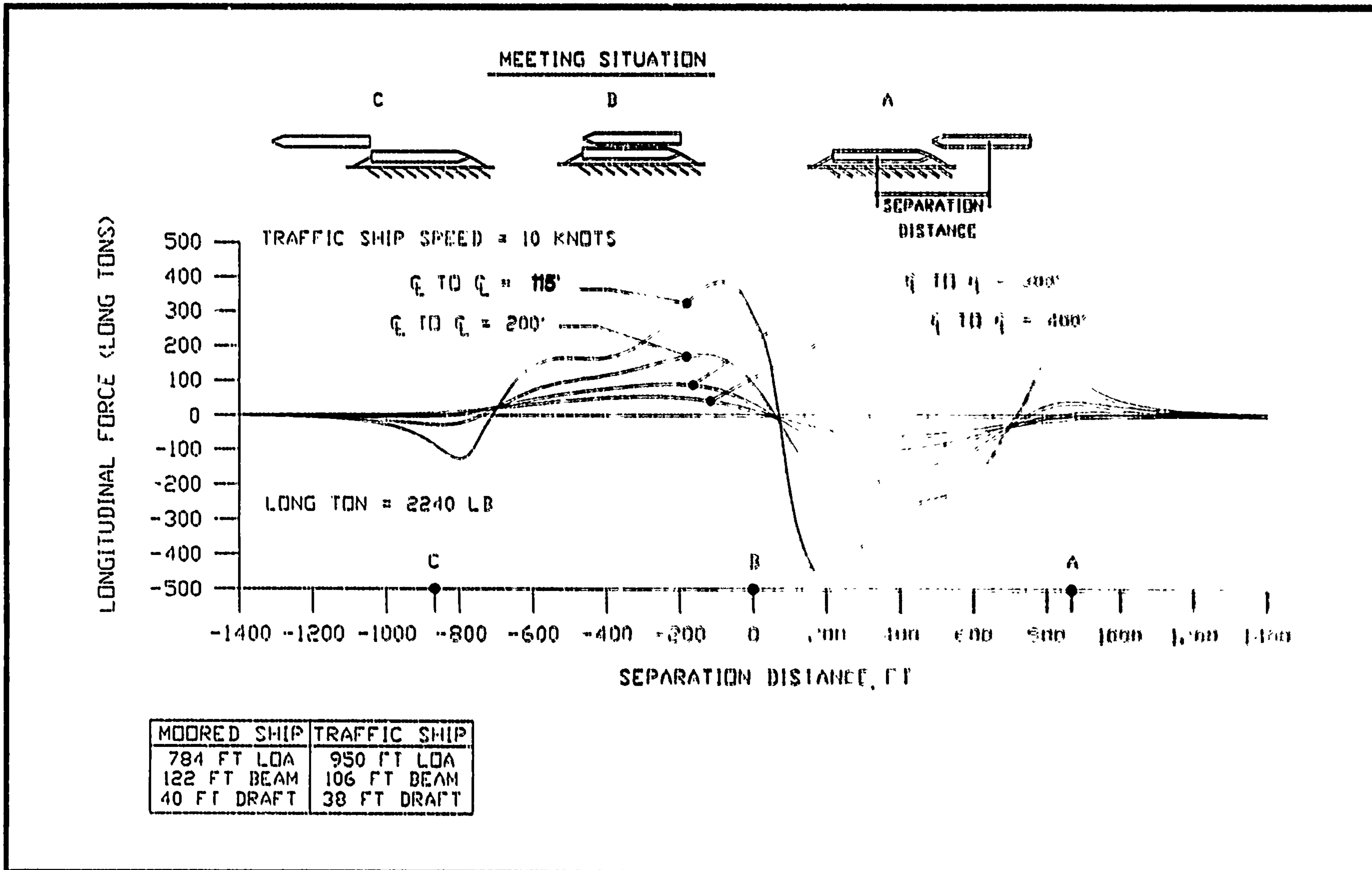
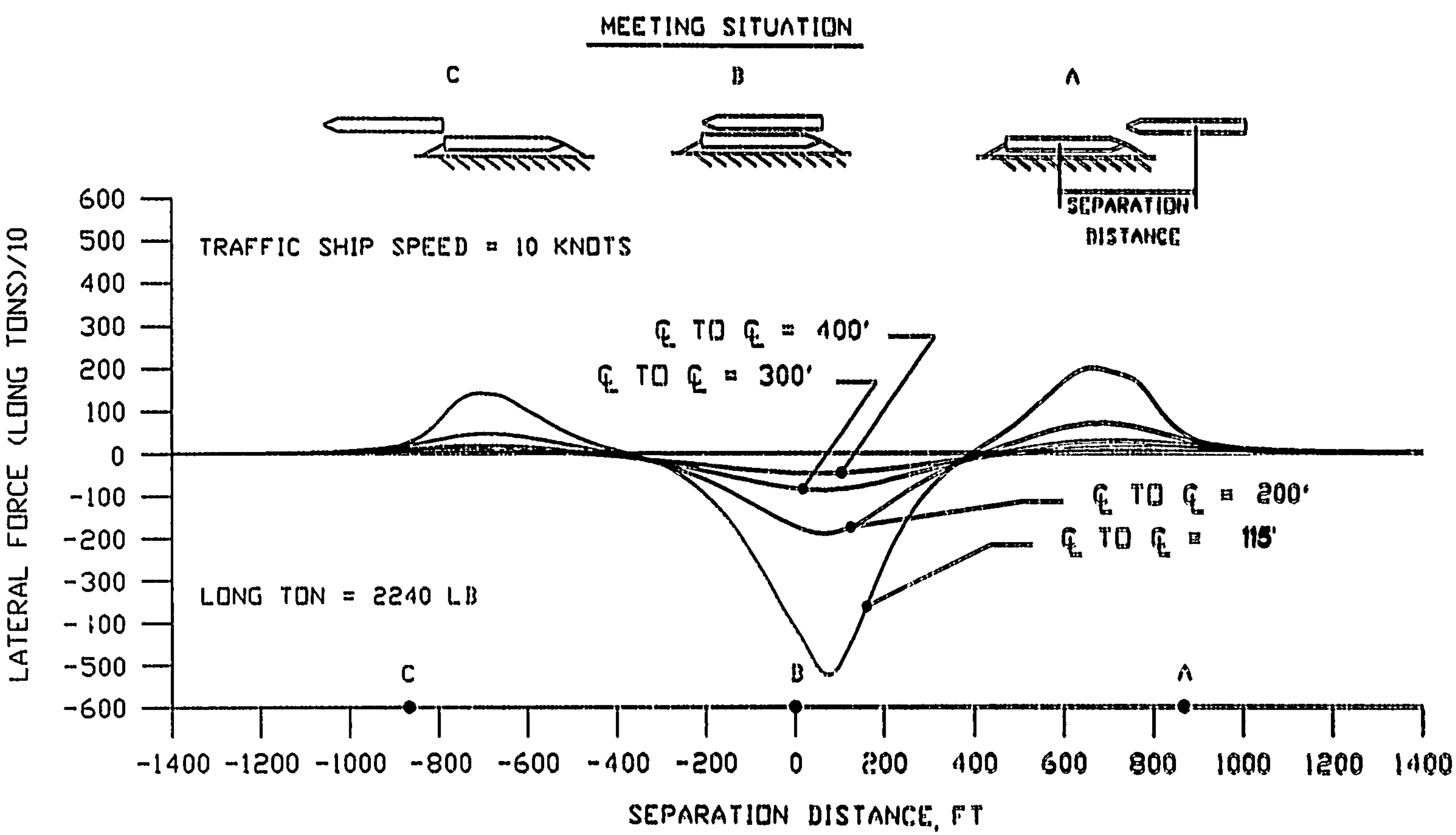
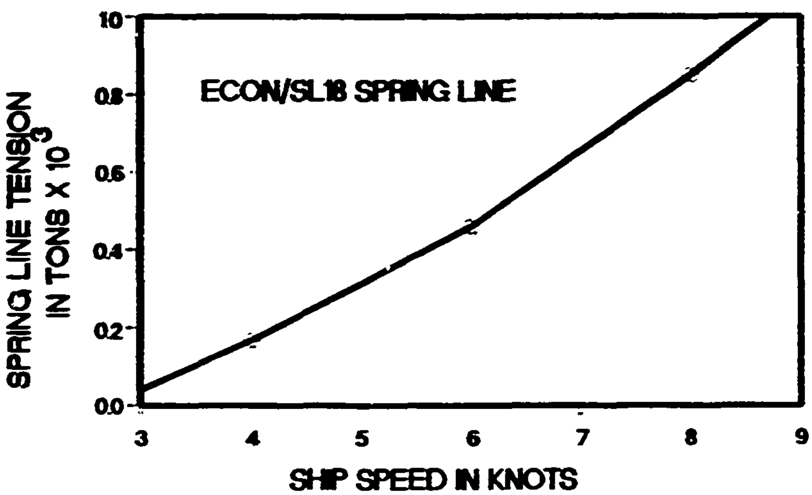


Figure 163. Ship/ship interaction, longitudinal force on moored ship, moored ship LOA 784 ft, traffic ship speed 10 knots, meeting configuration



MOORED SHIP	TRAFFIC SHIP
784 FT LOA 122 FT BEAM 40 FT DRAFT	950 FT LOA 106 FT BEAM 38 FT DRAFT

Figure 164. Ship/ship interaction, lateral force on moored ship, moored ship LOA 784 ft, traffic ship speed 10 knots, meeting configuration



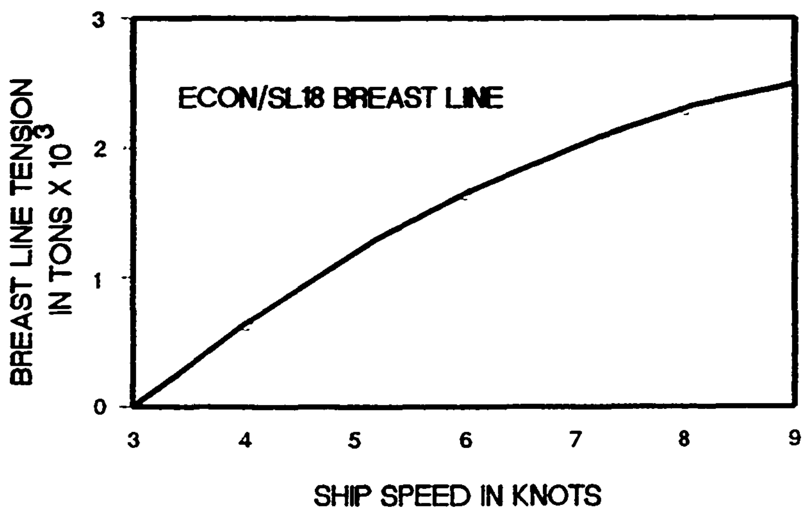


Figure 165. Line tension (from CAORF 1987)

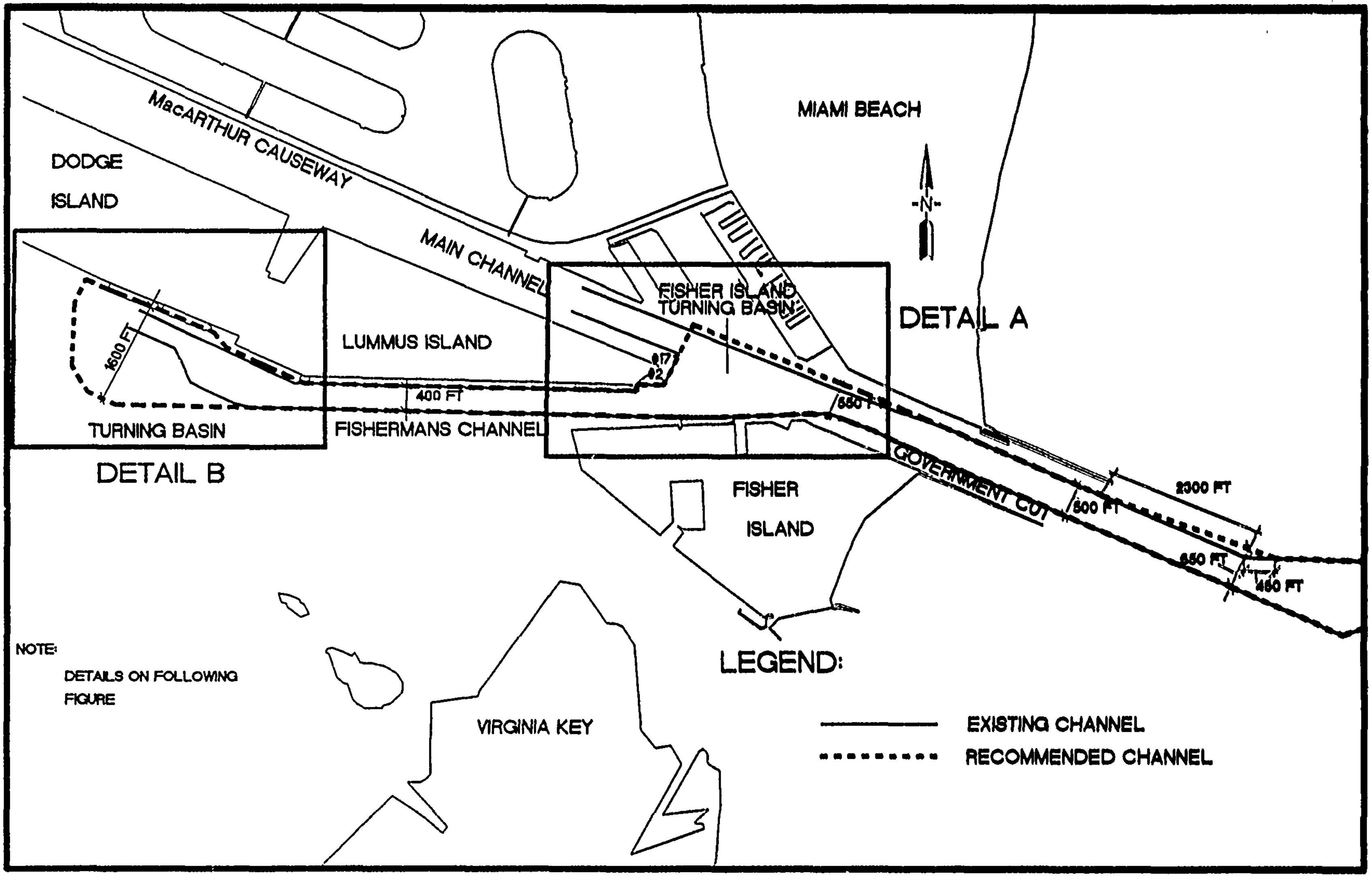
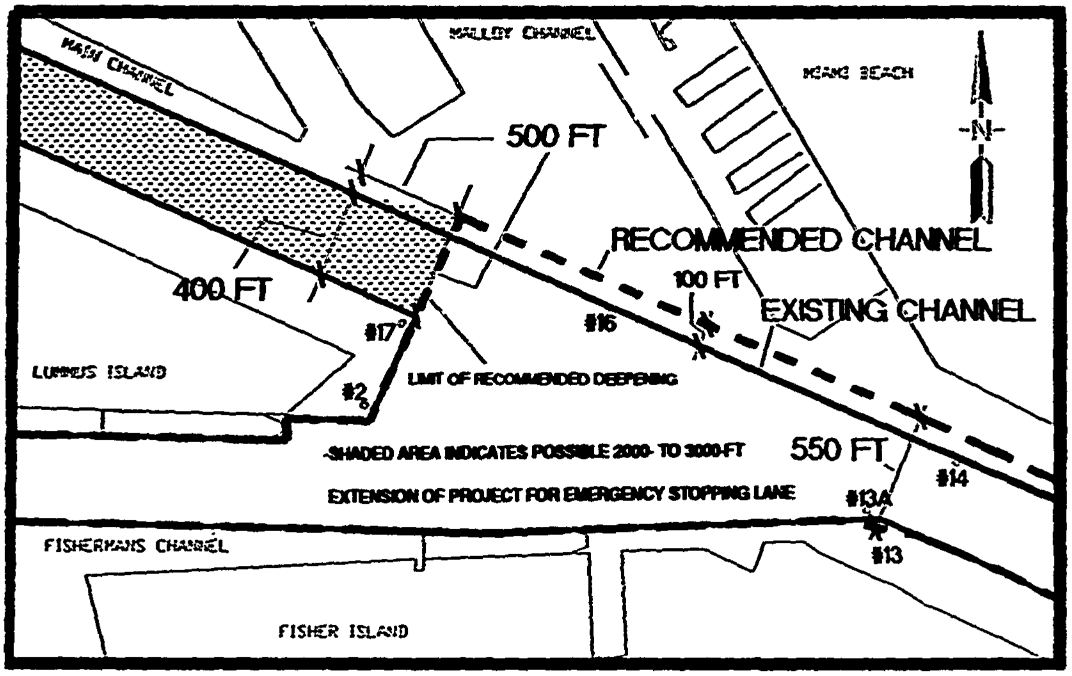
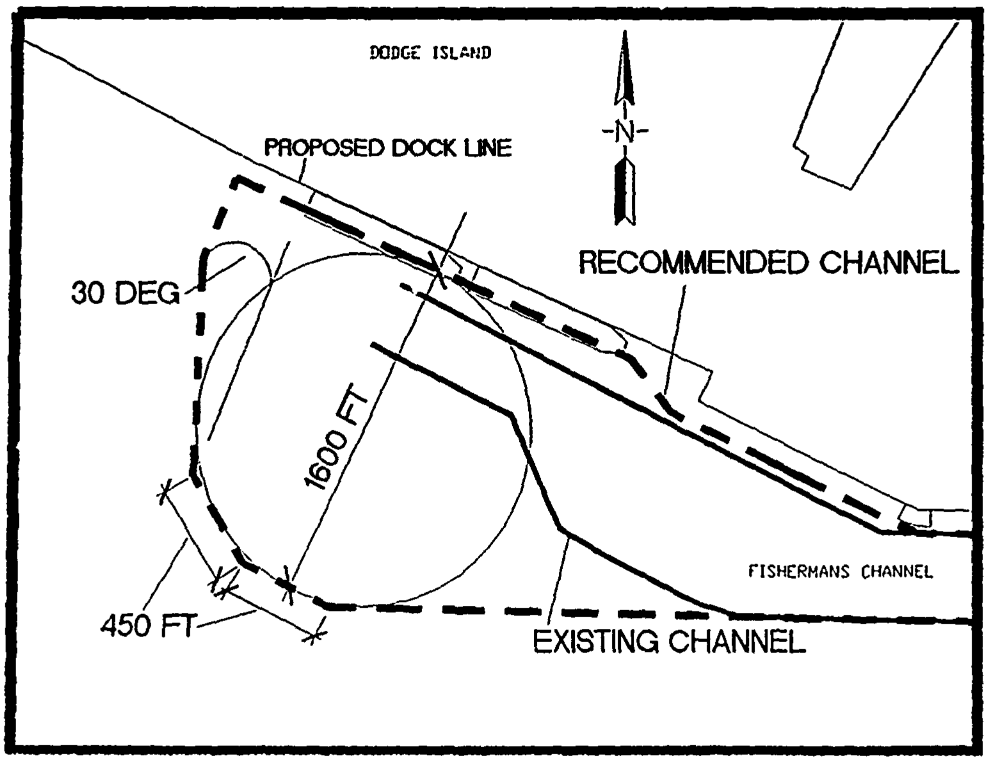


Figure 166. Recommended channel



a. Detail A



b. Detail B

Figure 167. Details of recommended channel